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THE FEASIBILITY OF OIL ANALYSIS FOR AIR FORCE DIESEL ENGINES

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This technical report has been reviewed and is approved for publication.

Walter M. Walden
USAF OAP Manager

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A feasibility study dealing with the implementation of an oil analysis program for Air Force diesel engines is described. Engine types were categorized and information assembled on characteristics, rebuild costs, and rebuild rates. Promising equipment classes for oil analysis were identified in this effort. A second task formulated a set of recommended analytical procedures based on a survey of current military and commercial practices in the area of oil analysis. An examination of the cost factors relevant to next page

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SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*) program implementation showed that the estimated savings/cost ratio is marginally attractive. Limiting the program to only selected equipment classes, it was estimated that a maximum return of $1.97 could be expected for each program dollar invested.

PREFACE

This final report was prepared by the Mobile Energy Division of Southwest Research Institute (SwRI). The effort was sponsored by the Directorate of Materiel Management, San Antonio Air Logistics Center (ALC), Kelly Air Force Base, Texas, under contract F41608-78-C-B224 for the period 18 September 1978 to 18 June 1979. The Air Force Project Monitor was Mr. Walter M. Walden, San Antonio ALC/MMETP. Mr. J.P. Cuellar, Jr., of SwRI, was technically responsible for the work.

The authors acknowledge the significant contributions to this work by Messrs. S.R. Westbrook, W.W. Hardaway, Sr., J.W. Pryor, and J.A. Kachich of SwRI. Special recognition is due to Messrs. Edwin C. Montgomery and Louis Alvarado of the Directorate of Maintenance at San Antonio ALC who provided much of the data and information pertinent to the task on engine classification. Finally, acknowledgement is given to the numerous military and industry personnel who provided the benefit of their background and experience to the study.

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INTRODUCTION

Some seventeen years ago the Air Force initiated a spectrometric oil analysis program applicable to aircraft in an effort designed to prevent engine failures, reduce accidents, and decrease maintenance requirements. Presently, spectrometric lubricant analysis for wearmetals monitors some 60,000 items of equipment, principally aeronautical, with a monthly workload near 120,000 samples. The success of the oil analysis program has been well demonstrated in terms of maintenance cost avoidances which, for calender year 1977, amounted to a value in excess of $51 million. A dollar-saving of this magnitude for aircraft equipment not only justifies the current program but also suggests a sizeable potential for increased savings through expansion of the program to include nonaeronautical equipment.

The Air Force Oil Analysis Program (OAP) Management Office recognized this potential, and identified diesel engines as an equipment class in the Air Force inventory with some probability of success in an expansion of the OAP to include nonaeronautical equipment. The work described herein was a feasibility study designed to explore the expected benefits from Air Force diesel engine oil analysis. Employing Air Force supplied records, engines were classified as to characteristics, end item, usage, and rebuild rates and costs for the period April 1977 through March 1979. A second task examined available information on current or promising analytical techniques and sampling procedures, in both commercial and military practice, applicable to diesel engine monitoring. From this examination, a set of analysis methods was formulated with emphasis on applicability, cost, and performance simplicity. Lastly, the economic factors relative to implementation of Air Force diesel engine oil analysis were considered.

SECTION II
ENGINE CLASSIFICATION

General

In 1977, early detection of impending failures of 1394 aircraft engines resulted in depot overhaul cost avoidances in excess of $51 million. The Air Force estimates that additional savings can be achieved through a comprehensive oil analysis program tailored specifically to the requirements of diesel engines currently in the Air Force inventory.

This section will discuss the methods utilized to collect sufficient data to facilitate categorizing Air Force diesel engines and provide other pertinent information in a manner that selection of engines to be placed in an oil analysis program could be systematically made.

Engine Performance Sources

To compile adequate information, numerous contacts and visits to Air Force installations were made. The following Air Force personnel were very cooperative and helpful in providing necessary records, so this information could be extracted:

Mr. Edwin C. Montgomery, San Antonio ALC, MMP
Mr. Louis Alvarado, San Antonio ALC, MMPRR
Mr. Ray Will, Sacramento ALC, MMIMB
Mr Sidney Morris, Warner Robins ALC, MMIRAB
Mr. Ollie Turner, Wright-Patterson AFB, LOWCS

Also, in addition to Air Force Logistics Command Centers, visits to other Air Force installations were made. Personnel contacted and corresponding installations were:

Mr. Robert Hunhke, Offutt AFB, LGTV
LTC E.L. Roberts, Little Rock AFB, 308th Missile Maint. Squadron

The above contacts plus contacts with various engine manufacturers/ dealers provided sufficient information for the compilation of data presented in Table 1.

It should be noted that during these visits, especially to Sacramento ALC, Offutt AFB and Little Rock AFB, it was discovered that a great number of engines, particularly generators are not on the "normal" Air Force inventory lists. These generators and engines are considered "Real Installed Property Equipment" and are under control of the various bases' Civil Engineers. It was concluded that in order to include these in the final document for selection of engines for an oil analysis program, visits to virtually every Air Force installation would be required. Therefore, since neither time nor funds would permit visits to every Civil Engineer Squadron in the Air Force, the "Real Installed Property Equipment" is not included in the information presented in Table 1.

Air Force Diesel Engine Types and Utilization

Table 1 presents complete descriptive information for diesel-powered end items currently in service in the Air Force. Engine descriptive material together with quantity in service, initial cost, engine rebuild cost, and number of each engine type rebuilt during the 2-year period April 1977 through March 1979 were derived from records made available by those individuals mentioned above.

In many cases, data for the number of engines rebuilt during these periods were not available, likely due to the fact that these specific end items were in very low usage during that time. It should be emphasized that the various subjective descriptive terms used to differentiate severity of service (L = low, M = moderate, H = high), have been based upon typical Air Force field utilization of each general class of end item; the range of severity varies dramatically when considering worldwide Air Force operations.

The end item types requiring overhaul, within the 2-year period covered by Table 1 were combined according to seven major categories, as shown in Table 2. The annual rebuild cost listed for each end item is the average of the

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA

Engine: Make	Model	Series	Part Number	Stock Number	No. of Cylinders	Disp. cu in	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Engine Rebuild Cost	No. Rebuilt Apr/Mar 77/78	No. Rebuilt Apr/Mar 78/79
Detroit	6028C	6-71	D664-1094	2815-00-009-2612	6	426	255	$ 7,276.00	12	3655-00-060-5355	Oxy & Nitrogen Plant	M	$5,650.00	6	7
Detroit	5043-7000	4-53	903-5850	2815-00-085-7610	4	212	130	3,842.00	124	3930-00-880-0466CT	Fork Lift-Adverse Terrain	M	2,700.00	29	26
Detroit	5043-7000	4-71	588X-101	2815-00-102-4961	4	284	165	5,280.00	6	5815-00-728-9788	Gen. Set	L		*	*
Caterpillar	D311	*	D311H	2815-00-106-3127	4	251	75	2,688.00	100	6115-00-881-5170	Gen. Set	L		*	*
Caterpillar	1673B	*	3R6942	2815-00-110-6269	6	638	250	6,413.00	37	1740-00-998-6280YW	MB-2 Towing Tractor	H	1,282.00	1	0
Detroit	*	4-71	13053	2815-00-125-3063	4	284	165	4,920.00	12	6115-00-847-7629	Gen. Set	L		*	*
Detroit	*	4-53	5043-7101	2815-00-131-7745	4	212	130	3,137.00	103	4310-00-595-3865	MC-5 AirCompressor	M	627.00	1	0
Detroit						212	130			4310-00-918-6925	Model GRP-1805				
Detroit						212	130			4310-00-959-1857	Model GRP-1913				
Detroit						212	130			4310-00-967-3087	Model GRP-2040				
Cummins	NH-220	*	990-46-78	2815-00-132-3900	6	743	220	3,704.00	4	6115-00-116-2218	Gen. Set EMU-23	L		*	*
Cummins	NHC-4-BI	*	990-46-80	2815-00-132-3901	4	495	125	3,759.00	35	6115-00-116-2217	Gen. Set EMU-22	M	751.80	4	10
Cummins		NRTO-6-B1	990-46-79	2815-00-132-9957	6	[illegible]3	335	6,673.00	17	6115-00-116-2219	Gen. Set EMU-24	M	3,800.00	4	1
Hercules	D-298	*	D298ERX15	2815-00-132-9960	6	298	90	2,321.00	412	6115-00-118-7646	Gen. Set EMU-21	M	2,500.00	3	0
Detroit	5033-7201	3-53	57803-10	2815-00-135-5465	3	159	97	4,428.00	288	4920-00-928-4726	Gen. Set	L		*	*
Certist	33-4-7	*	33-4-7	2815-00-150-7628	3	*	*	3,262.00	180	4930-00-134-4822	Hydrant-Refueling System	L	2,200.00	*	*
Certist						*	*			4930-00-857-8585	Hydrant-Refueling System				
Caterpillar	3160	*	64-7-588-1	2815-00-161-1639	8	636	210	5,070.00	33	3930-00-481-5105CT	40K Loader	M	3,802.00	2	5
Caterpillar	D343	*	3R8760	2815-00-161-1646	6	893	420	12,609.00	115	3825-00-102-5081	Snow Plow-Rotary 34,000 GVW	H	2,521.80	1	0
Caterpillar						893	420			3825-00-172-8779	Snow Plow-Rotary 34,000GVW				
Caterpillar						893	420			3825-00-172-8780	Snow Plow-Rotary 34,000 GVW				
Caterpillar						893	420			3825-00-954-6867	Snow Plow-Rotary 34,000 GVW				
Caterpillar	1673C	*	5R1917	2815-00-162-6606	6	638	250	8,137.00	133	3825-00-063-6048	Snow Plow-Rotary & Disp. 36,000 GVW	H	1,627.40	1	0
						638	250			3825-00-102-5081	Snow Plow-Rotary & Disp. 36,000 GVW				
						638	250			3825-00-102-7808	Snow Plow-Rotary & Disp. 36,000 GVW				
						638	250			3825-00-172-8778	Snow Plow-Rotary & Disp. 36,000 GVW				
						638	250			3825-00-172-8780	Snow Plow-Rotary & Disp. 36,000 GVW				
						638	250			3[illegible]-00-226-4116	Snow Plow-Rotary & Disp. 36,000 GVW				
						638	250			3825-00-402-6704	SnowPlow-Rotary & Disp. 36,000 GVW				
Caterpillar	1693T	*	3R9827	2815-00-163-2897	6	893	325	12,000.00	255	3825-00-104-5246	Snow Plow-Disp. 54,000 GVW	H	2,500.00	2	2
Caterpillar						893	325			3825-00-140-3012	Snow Plow-Disp. 54,000 GVW				
Caterpillar						893	325			3825-00-150-7140	Snow Plow-Disp. 54,[illegible] GVW				
Caterpillar						893	325			3825-00-150-7141	Snow Plow-Disp. 54,[illegible] GVW				
Caterpillar						893	325			3825-00-150-7142	Snow Plow-Disp. 54,[illegible] GVW				
Caterpillar						893	325			3825-00-150-7143	S[illegible] Plow-Disp. 54,000 GVW				
Caterpillar						893	325			3825-00-192-0727	Snow Plow-Disp.54,000 GVW				
Caterpillar						893	325			3825-00-233-2518	Snow Plow-Disp. 54,000 GVW				
Cummins	NHC-4-BI	*	99047-16	2815-00-176-3664	4	495	125	4,286.00	244	6115-00-233-6444	MB-17 Gen. Set	M	857.20	1	0
Cummins	NH-220	*	99047-17	2815-00-176-3665	6	743	220	7,062.00	69	6115-00-689-4488	MB-16 Gen. Set	M	2,200.00	*	*
Cummins	NRTO-6-BI	*	99047-18	2815-00-176-3666	6	743	335	6,098.00	188	6115-00-689-4489	MB-15 Gen. Set	M	4,573.00	4	8
Hercules	D298	*	D298ERX26	2815-00-176-3667	6	298	90	3,120.00	349	6115-00-689-4485	MB-18 Gen. Set	M	2,500.00	8	16
Hercules	D198	*	D198ERX36	2815-00-176-3668	4	198	72	1,914.00	110	6115-00-689-4486	MB-19 Gen. Set	M	382.80	4	0

*Information not determined.

**L = Low, M = Moderate, H = High.

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA (Cont'd)

Engine														No. Rebuilt	
Make	Model	Series	Part Number	Stock Number	No. of Cylinders	Disp, cu in.	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Engine Rebuild Cost	Apr/Mar 77/78	Apr/Mar 78/79
Caterpillar	D333C	*	3R7975	2815-00-193-6809	6	638	190	*	*	*	MC-6 Air Compressor Davey	L	*	*	*
Caterpillar	D333T	*	70/4013	2815-00-195-4128	6	638	250	$ 6,811.00	12	6115-00-133-9101	MEP 100 kW Gen. Set	M	$1,362.20	1	0
Caterpillar						638	250			6115-00-133-9102	MEP 100 kW Gen. Set				
Caterpillar						638	250			6115-00-133-9103	MEP 100 kW Gen. Set				
Caterpillar	D343TA	*	5R1946	2815-00-202-2437	6	893	420	13,418.00	396	4210-00-495-9119	P-4 Firetruck	M	9,750.00	10	9
Caterpillar						893	420			4210-00-184-6415	P-4 Firetruck				
Caterpillar	D343TA	*	70/4014	2815-00-212-0527	6	893	420	10,720.00	38	6115-00-133-9104	MEP 200 kW Gen. Set	M	2,144.00	1	1
Caterpillar						893	420			6115-00-935-8729	MEP 200 kW Gen. Set				
Allis-Chalmers	6DC844	*	6DC844	2815-00-339-5967	6	844	235	5,317.00	160	6115-00-526-0114	PU 361 Gen. Set	L		*	*
Allis-Chalmers			024BMD			844	235								
Allis-Chalmers			7083A			844	235								
Allis-Chalmers			(09367)			844	235								
Allis-Chalmers			(81366)			844	235								
Detroit	*	3-53	5033-7001	2815-00-369-4994	3	159	97	4,635.00	0	4320-00-131-9185	R-22 Pumping Unit	L	927.00	*	*
Detroit						159	97			4320-00-32[illegible]-8620	R-22 Pumping Unit				
Certist	43-5	*	43-5	2815-00-420-6175	4	*	*	4,550.00		4320-00-924-6416	A/M 32R-33-22 Pumping Unit	L	910.00	*	*
IHC	DT429	*	701129C91	2815-00-455-5550	6	*	*	5,074.00	203	2410-00-740-0290	TD-20B Crawler Tractor & 250 Loader	H	2,850.00	1	0
IHC						*	*			2410-00-756-1161YW	TD-20B Crawler Tractor & 250 Loader				
IHC						*	*			2410-00-927-5383	TD-20B Crawler Tractor & 250 Loader				
IHC						*	*			2410-00-928-7491	TD-20B Crawler Tractor & 250 Loader				
IHC						*	*			2410-00-973-1864	TD-20B Crawler Tractor & 250 Loader				
IHC						*	*			3805-00-785-5905	TD-20B Crawler Tractor & 250 Loader				
Caterpillar	D-348	*	3R8954	2815-00-485-1072	12	1787	850	33,354.00	80	3852-00-104-5426	54000 Snow Plow	H	6,670.80	2	5
Caterpillar						1787	850			3852-00-126-5784	54000 Snow Plow				
Caterpillar						1787	850			3852-00-126-5785	54000 Snow Plow				
Caterpillar						1787	850			3852-00-150-7142	54000 Snow Plow				
Caterpillar						1787	850			3852-00-150-7143	54000 Snow Plow				
Caterpillar	D-346TA	*	3R7280	2815-00-487-5966	8	1191	565	22,519.00	48	1740-00-101-9256	A/S32V-30 Tow Tractor	L		*	*
Caterpillar						1191	565			1740-00-101-9256Y	A/S32V-30 Tow Tractor				
Hercules	D-298	*	D298ERX37	2815-00-501-7001	6	298	90	2,846.00	71	6115-00-118-1241	DOD 30 kW Gen. Set	M	569.00	0	1
Hercules						298	90			6115-00-118-1247	DOD 30 kW Gen. Set				
Hercules						298	90			6115-00-118-1248	DOD 30 kW Gen. Set				
Euclid	6080	6-71	5111427	2815-00-528-6457	6	426	255	5,920.00	138	1740-00-287-6967YW	MB-2 Tow Tractor	H	3,651.00	2	5
Euclid						426	255			1740-00-540-6428YW	MB-2 Tow Tractor				
Hercules	D-198	*	D198ERX51	2815-00-530-8742	4	198	61	2,430.00	71	6115-00-118-1241	DOD 15 kW Gen. Set	M	530.60	1	1
										6115-00-118-1244	DOD 15 kW Gen. Set				
										6115-00-118-1245	DOD 15 kW Gen. Set				
Hercules	DIX4D	*	DIXDSO60006	2815-00-555-5993	4	166	57	2,853.00	486	6115-00-067-5188	MB-5 Gen. Set	M	2,100.00	0	2
Hercules						166	57			6115-00-504-1401	MB-5 Gen. Set				

*Information not determined.

**L = Low, M = Moderate, H = High.

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA (Cont'd)

Make	Model	Series	Engine Part Number	Engine Stock Number	No. of Cylinders	Disp. cu in.	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Engine Rebuild Cost	No. Rebuilt Apr/Mar 77/78	No. Rebuilt Apr/Mar 78/79
Caterpillar	3306	*	5R3420	2815-00-610-7598	6	638	245	$ 7,462.00	40	3825-00-063-6048	Snow Plow-34,000 GVW Rotary & Disp.	H	$ 973.20	0	1
Caterpillar						638	245			3825-00-102-7808	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-172-8780	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-554-4987	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-663-7959	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-842-2209	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-842-2210	Snow Plow-34,000 GVW Rotary & Disp.				
Caterpillar						638	245			3825-00-954-6867	Snow Plow-34,000 GVW Rotary & Disp.				
Cummins	NRTO-6-BI	*	99016-88	2815-00-809-9794		743	335	6,561.00	28	3810-00-580-2993	MB-1A Crane	M	4,921.00	0	2
IHC	DT573	*	332426R91	2815-00-848-1594	8	573	260	6,210.00	29	3805-00-078-5900	Model 270 Pay Scraper	M	5,800.00	6	3
Allis-Chalmers	21000H	*	438F471	2815-00-848-1665	6	850	350	9,377.00	31	2410-00-921-6888	Model HD21P Tractor	M	5,900.00	5	0
Cummins	NH220	*	99040-7[illegible]	2815-00-888-2425	6	743	220	4,585.00	100	1740-00-847-5319YW	MB-2 Tow Tractor (Con-Diesel)	M	917.00	0	3
Cerlist	33-4-3	*	33-4-3	2815-00-927-2355	3	*	*	3,020.00	109	4930-00-134-4822	A/E-32R-14 Hyd. Refueling Sys.	L	2,200.00	*	*
										4930-00-857-8585					
Detroit	3914	3-71	3914 Spec 80001	2815-00-933-3212	3	213	120	2,887.00	0	3930-00-134-9230	QS-3354 Fork Lift	M	577.40	6	3
Detroit						213	120			3930-00-879-2157	QS-3354 Fork Lift				
Detroit						213	120			3930-00-935-7975	QS-3354 Fork Lift				
Detroit						213	120			3930-00-988-5373CT	QS-3354 Fork Lift				
GMC	*	12V-71	65D42006	2815-00-933-5487	12	852	340	18,974.00	132	6115-00-464-9442	EMU-17 Gen. Set	L	*	*	*
GMC						852	340			6115-00-914-3444	EMU-17 Gen. Set				
GMC						852	340			6115-00-464-9443	EMU-17 Gen. Set				
GMC						852	340			6115-00-914-3447	EMU-17 Gen. Set				
GMC						852	340			6115-00-832-4859	EMU-17 Gen. Set				
GMC						852	340			6115-00-832-4894	EMU-17 Gen. Set				
GMC	6045N	6-71	65D42204	2815-00-933-5488	6	426	255	9,365.00	65	6115-00-464-9441	EMU-16 Gen. Set	M	1,873.00	1	0
GMC						426	255			6115-00-914-3445	EMU-16 Gen. Set				
GMC	3045C RC	3-71	65D42002	2815-00-933-5490	3	213	120	5,723.00	62	6115-00-456-9440	EMU-15 Gen. Set	M	1,144.60	3	1
GMC						213	120			6115-00-912-4730	EMU-15 Gen. Set				
Hercules	D198	*	D198ERX13	2815-00-934-7876	4	198	72	2,244.00	598	6115-00-937-3523	MB-5A Gen. Set	M	1,900.00	3	9
Hercules						198	72			6115-00-967-4482	MB-5A Gen. Set				
Hercules						198	72			6115-00-999-2659	MB-5A Gen. Set				
Cummins	NHC-4-BI	*	99036-49	2815-00-938-0586	4	495	125	3,761.00	141	3805-00-702-0898	440 Road Grader	M	3,150.00	15	11
Cummins										3805-00-900-7596	440 Road Grader				
Cummins										3805-00-978-9311	440 Road Grader				
Cummins										3805-00-978-9312	440 Road Grader				
Onan	DRNMS	*	DRNMS-701/C	2815-00-951-6888	Opposed 2	60	10.4	1,550.00	19	6115-00-847-2746	PU-362/M Gen. Set	L	*	*	*
Cummins	NRTO-6-BI	*	99042-74R	2815-00-965-1001	6	743	335	5,470.00	340	6115-00-081-2036	MB-15 Gen. Set	M	4,850.00	1	0
Cummins	NH-220-BI	*	99042-76R	2315-00-965-1002	6	743	220	4,816.00	315	6115-00-081-2030	MB-16 Gen. Set	M	3,200.00	1	4
Cummins	NHC-4-BI	*	99042-75R	2815-00-965-1006	4	495	125	4,705.00	600	6115-00-064-8168	MB-17 Gen. Set	M	3,000.00	1	3

*Information not determined.

**L = Low, M = Moderate, H = High.

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA (Cont'd)

Make	Engine Model	Engine Series	Engine Part Number	Engine Stock Number	No. of Cylinders	Disp, cu in.	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Engine Rebuild Cost	No. Rebuilt Apr/Mar 77/78	No. Rebuilt Apr/Mar 78/79
Cummins						495	125			6115-00-081-2034	MB-17 Gen. Set				
Hercules	D-298	*	D298ERX11	2815-00-965-1014	6	298	90	$ 3,586.00	558	6115-00-081-2031	MB-18 Gen. Set	M	$2,900.00	9	9
Hercules						298	90			6115-00-807-5047	MB-18 Gen. Set				
Hercules	D-198	*	D198ERX-18	2815-00-999-1589	4	198	72	3,011.00	222	6115-00-081-2035	MB-19 Gen. Set	M	402.20	1	1
Hercules						198	72			6115-00-837-5049	MB-19 Gen. Set				
Cummins	210	504C	34150000	2815-01-021-9575	8	504	210	3,708.00	111	3930-00-102-4236CT	40K Loader 463 System	H	741.60	3	6
Cummins						504	210			3930-00-800-3929CT	40K Loader 463 System				
Caterpillar	3463	*	5R3531	2815-01-026-4289	6	893	375	11,977.00	500	3825-00-104-5426	Snow Plow-54,000 GVW Disp.	H	2,395.40	0	5
Caterpillar						893	375			3825-00-126-5784	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-126-5785	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-140-3022	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-150-7140	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-150-7141	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-150-7142	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-150-7143	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-192-0727	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-233-2518	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-542-2553	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-542-2554	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-542-2804	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-555-8244	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-555-8245	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-725-9184	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-725-9185	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-7346	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-7348	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3225-00-912-7349	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-7350	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-7351	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-7352	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-912-8486	Snow Plow-54,000 GVW Disp.				
Caterpillar						893	375			3825-00-961-2926	Snow Plow-54,000 GVW Disp.				
Caterpillar	D346TA	*	3R7280	2815-00-487-5966	8	1191	565	22,519.00	35	1740-00-101-9256	A/S32U-30 Tow Tractor (C-5A)	L	*	*	
Detroit	6037	6-71	EE-101-A-155	2815-00-540-5071	6	284	165	4,681.00	1	3655-00-141-8840	A-1A Lox Gen.	L	*	*	*
Detroit						284	165			3655-00-200-1949	A-1A Lox Gen.				
Detroit						284	165			3655-00-589-6277	A-1A Lox Gen.				
Monarch	CSR-3	*	08103-100	2815-00-702-2608	3	155	19.5	2,277.00	240	6115-00-964-3040	EMU-19V Gen. Set	M	1,707.00	4	2
J.I. Case	M-64BHD	*	A67037	2815-01-037-7486	*	504	180	6,367.00	4	4130-01-016-3046	Cooling Cart	*	1,273.40	0	0
ACEC[1]	*	*	6901REVA	2815-01-040-1502	*	*	*	972.00	20	4120-00-349-2525	PTO Air. Cond. Trailer	*	194.46	0	0

*Information not determined.

**L = Low, M = Moderate, H = High.

(1) Accessories Control and Equipment Corporation.

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA (Cont'd)

			Engine										Engine	No. Rebuilt	
Make	Model	Series	Part Number	Stock Number	No. of Cylinders	Disp cu in.	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Rebuild Cost	Apr/Mar 77/78	Apr/Mar 78/79
Caterpillar	3208	•	583409	2815-01-042-7450	8	636	210	$ 5,359.00	40	3930-01-008-7889CT	40K Loader	M	$1,279.80	0	3
Caterpillar			61/7/588A1			636	210	10,335.00	12	6115-00-139-9101	100 kW MEP Gen. Set	M	2,067.00	0	0
Caterpillar	D-333	•	5R3635	2815-01-040-3662	6	638	250			6115-00-139-9102	100 kW MEP Gen. Set				
Caterpillar						638	250			6115-00-139-9103	100 kW MEP Gen. Set				
Caterpillar						638	250	•	3433	2320-00-540-3963	M35A-2 Truck 2 1/2 Tons	L	•	•	•
Continental	LDS-427-2	•	10898701	2815-00-897-5061	6	427	140			2320-00-554-8289	M52A-2 Truck 5 Tons				
Continental						427	140			2320-00-055-9258	M543A-2 Wrecker		•	•	•
Continental						427	140	•	•	3820-00-788-5999	Crusher Roller	L	•	•	•
Continental	•	•	SD802-286	2815-00-745-8972	•	427	140	•	92	3930-00-322-9203CT	K-Loader Aircraft Cargo Handling Trk.		•	•	•
Cummins	210	•	•	•	8	504	210	•	23	3895-00-043-3926YW	Compactor, Paddle Foot Model 3.30	•	•	•	•
GMC	6V53	•	•	•	6	284	185	•	45	3810-00-489-6744	Crane-Shovel, Crawler Mounted	•	•	•	
GMC	3-71N	•	•	•	3	212.8	118	•	15	3810-00-192-5320YW	Crane-Shovel, Crawler Mounted	L	•	•	•
GMC	4057C	4-71	5172559R	2815-00-445-5425	4	284	165	•	12	3810-00-489-6746YW	Crane-Shovel, Crawler Mounted	•	•	•	•
GMC	6-71N	•	•	•	6	425.6	218	•	21	3805-00-197-4184YW	Road Grader, Model 12L	L	•	•	•
Caterpillar	D-333	•	3R712	2815-00-965-0226	6	638	250	•	183	3805-00-995-3236YW	Tractor-Payloader, Model H90-CML	L	•	•	•
Cummins	JT-6-BI	•	99044-31R	2815-00-965-1005	6	•	•	•	23	3805-00-067-4734YW	Pay Hauler, Model 65B	L	•	•	•
IHC	DVT-573	•	343R91	2815-00-891-0336	8	573	260	•	2	3820-00-641-8141YW	Crushing & Screening Plant 25 cu yd/hr	•	•	•	•
GMC	3031C	•	•	•	•	•	•	•	99	2410-00-057-4897YW	Tractor Crawler Model TD-25B	L	•	•	•
IHC	DT-817	•	670946C91	2815-00-434-6359	6	817	329	•	19	2420-00-930-5999YW	Tractor, Dozer Model Cat 830MB	•	•	•	•
Caterpillar	D-343-T/A	•	•	•	6	893	420	•	234	2410-00-267-0002YW	Tractor, Track Laying Model D-6	•	•	•	•
Caterpillar	D-333	•	3R322	2815-00-965-0224	6	638	250	•	6	2410-00-233-5750YW	Tractor, Track Laying Model D-8	•	•	•	•
Caterpillar	D-342	•	3R2980	2815-00-965-0223	6	1246	320	•	1054	2420-00-177-7241YW	Tractor, Industrial, Wheeled, Model 1W55	•	•	•	•
Perkins	A4236	•	•	•	4	•	•	•	789	2420-00-157-0754YW	Tractor, Industrial, Wheeled, Size 5	•	•	•	•
Fomoco	3500/4500	•	•	•	3	•	•	•	86	3805-00-234-9776YW	Traxcavator, Model 977K	•	•	•	•
Caterpillar	D-333	•	•	•	6	638	250	•	24	3805-00-050-9968YW	Trencher, Self Propelled Model 724-L	•	•	•	•
IHC	UD-236	•	•	•	6	236	71	•	•	3805-00-050-9968YW	Trencher, Self Propelled Model 724-L	•	•	•	•
GMC	3-53	•	•	•	3	159	97	•	379	1740-00-287-6967YW	Acft. Towing Tractor Type MB-2	•	•	•	•
Detroit	6-71RA	•	•	•	6	426	255			1740-00-540-6428YW	Acft. Towing Tractor Type MB-2				
Detroit						426	255	•	774	2320-00-138-3006	Fuel Servicing Tank Truck, Type A/S32R-9	•	•	•	•
Cummins	V8-210	V504	•	•	8	504	183	•	512	2320-00-086-7480YW	Tractor, Truck 5 Ton 6 × 6 Model M52A1	•	•	•	•
Mack	ENDT-673	•	•	•	6	673	211			2320-00-086-7479YW	Tractor, Truck 5 Ton 6 × 6 Model M52A1	•			
Mack						673	211	•	134	2320-00-892-1971YW	Tractor Truck, 15 Ton 6 × 4 Model D-450-T	•	•	•	•
Detroit	7087	•	•	•	8	568	350	•	•	2320-00-752-9557YW	Tractor Truck, 15 Ton 6 × 4 Mod. 921DNTSQHD	•	•	•	•
Cummins	NTO-280	•	•	•	6	•	•	•	300	4210-00-897-6190	Truck-Crash, Fire & Rescue Type A/S32P2	•	•	•	•
Detroit	8V71	•	•	•	8	568	350	•	5	3930-01-015-3965	Truck, Forklift 10,000	•	•	•	•
Detroit	•	4-53M	•	•	4	212	140	•	48	3805-01-032-9974	Trencher	•	•	•	•
J.I.Case	207	•	•	•	•	•	•	•	4	2320-01-039-7929	Truck-Van w/Car 24000G 4 × 2	•	•	•	•
IHC	D-190	•	•	•	•	•	•	•	372	2310-01-037-0392	Bus-Motor Sch 44PAX 4 × 2	•	•	•	•
IHC	D-190	•	•	•	•	•	•	•	•	2310-01-037-0392	Bus-Motor Sch 44PAX 4 × 2	•	•	•	•

*Information not determined.

**L = Low, M = Moderate, H = High.

TABLE 1. AIR FORCE DIESEL ENGINE/END ITEM INVENTORY DATA (Cont'd)

Make	Model	Engine Series	Engine Part Number	Engine Stock Number	No. of Cylinders	Disp. cu in.	H.P.	Initial Cost	No. in Service	Stock No. of End Item	Identification of End Item	Service Usage**	Engine Rebuild Cost	No. Rebuilt Apr/Mar 77/78	No. Rebuilt Apr/Mar 78/79
IHC	DT-466	*	*	*	*	466	231	*	*	2310-01-037-0392	Bus-Motor Sch 44PAX 4 × 2	*	*	*	*
IHC	D-150	*	*	*	*	*	*	*	39	2310-01-037-0393	Bus-Motor Sch 28PAX 4 × 2	*	*	*	*
Cummins	V-504	*	*	*	*	504	210	*	2274	2320-00-435-5695	Truck-Tank 5,000 gal.	*	*	*	*
Cummins	V-555	*	*	*	*	555	240	*		2320-00-433-5695	Truck-Tank 5,000 gal.	*	*	*	*
GMC	*	8V71N	*	*	*	568	350	*	972	2320-00-396-2052	Truck Tractor 44,500 GVW 6 × 4	*	*	*	*
GMC	*	6V92-TAC	*	*	*	*	*	*		2320-00-396-2052	Truck Tractor 44,500 GVW 6 × 4	*	*	*	*
Cummins	*	NTCC-250	*	*	*	855	235	*		2320-00-396-2052	Truck Tractor 44,500 GVW 6 × 4	*	*	*	*
IHC	DT-466	*	*	*	*	466	231	*	228	2320-00-477-5489	Truck Wrecker 44,500 GVW 6 × 4	*	*	*	*
Mack	ENDT-673	*	*	*	*	673	211	*	32	2320-00-605-6140	Truck Tractor 44,500 GVW 6 × 4	*	*	*	*
Detroit	6080	6-71	5111427	2815-00-528-6457	6	426	255	*	479	1740-00-143-8464YW	Tractor-Acft. Towing MB-2	*	*	*	*
Cummins	NH-220	*	99040-75	2815-00-888-2425	6	743	220	*		1740-00-143-8464YW	Towing-Acft. Towing MB-2	*	*	*	*
Caterpillar	1673-B	*	3R6942	2815-00-110-6269	6	638	250	*		1740-00-143-8464YW	Tractor-Acft. Towing MB-2	*	*	*	*
Caterpillar	3208-175	*	*	*	8	636	175	*		1740-00-143-8464YW	Tractor-Acft. Towing MB-2	*	*	*	*
IHC	D-190	*	*	*	*	*	*	*	1095	2320-00-611-2429	Truck-Tractor 24000G 4 × 2	*	*	*	*

*Information not determined.

**L - Low, M = Moderate, H = High.

TABLE 2. REBUILD COSTS BY EQUIPMENT TYPE

End Item	No. in Service as of March 79	Average Failures per Year	Annual Rebuild Cost, $K
Generator Sets			
DOD 15 kW	71	1	0.55
DOD 30 kW	71	0.5	0.30
EMU-15	62	2	2.30
EMU-16	65	0.5	0.95
EMU-19 V	240	3	5.10
EMU-21	412	1.5	3.75
EMU-22	35	7	5.25
EMU-24	17	2.5	9.50
MB-5	486	1	2.10
MB-5A	598	6	11.40
MB-15	528	6.5	29.85
MB-16	315	2.5	8.00
MB-17	844	2.5	6.45
MB-18	907	21	56.10
MB-19	332	3	1.15
MEP-100 kW	12	0.5	0.70
MEP-200 kW	38	1	2.15
Total	5033	62.00	145.60
Snow Plows			
Rotary, 34000 GVW	115	0.5	1.25
Rotary & Disp, 34000 GVW	40	0.5	0.50
Rotary & Disp, 36000 GVW	133	0.5	0.80
Rotary, 54000 GVW	580	5	26.95
Rotary & Disp, 54000 GVW	225	2	5.00
Total	1123	8.5	34.50
Loading Vehicles			
40K Loader	184	9.5	18.55
Fork Lift, Adverse Terrain	124	27.5	74.25
TD-20B Crawler Tractor & 250 Loader	203	0.5	1.90
Total	511	37.5	94.70
Towing Vehicles			
HD 21P Tractor	31	2.5	14.75
MB-2 Tow Tractor	275	5	14.85
Total	306	7.5	29.60
Fire Trucks			
P-4 Firetrucks	396	9.5	92.60
Total	396	9.5	92.60

TABLE 2. REBUILD COSTS BY EQUIPMENT TYPE (Cont'd)

End Item	No. in Service as of March 79	Average Failures per Year	Annual Rebuild Cost, $K
	Construction Vehicles		
MB-1A Crane	28	1	4.90
270 Pay Scraper	29	4.5	26.10
440 Road Grader	141	13	40.95
Total	198	18.5	71.95
	Facility Equipment		
MC-5 Air Compressor	103	0.5	0.30
Oxygen-Nitrogen Plant	12	6.5	36.70
Total	115	7.0	37.00
Overall Total	7682	148	505.95

April 1977 to March 1979 period. These data, along with those given in Table 1, will be used in the following section of the report to identify those item categories offering the greatest potential for a cost effective oil analysis program.

Equipment Selection

The end item populations by major category are depicted graphically in Figure 1. Obviously, generator sets are the dominant class with over 5,000 currently in the Air Force inventory. Figure 2 shows a corresponding bar chart of rebuild rate for each engine class during the period April 1977 through March 1979. Rebuild rate has been calculated as the ratio of end items requiring depot level rebuild to the total number of end items in each equipment type. In Figure 2, loading vehicles and construction vehicles can clearly be seen as the dominant classes, having high engine maintenance requirements. Figure 3 presents annual total rebuild costs which is the sum of annual rebuild costs for each of the specific line items within a given equipment type grouping. Generator sets dominate this chart largely because of the high number in the inventory, but now such relatively small classes as loading vehicles, fire trucks, and construction vehicles can be seen to emerge as costly equipment classes, emphasizing that these highly specialized items require special maintenance attention, resulting in a disproportionate cost to the Air Force. When total rebuild costs are divided by the number of equipment items (Fig. 3 and 1, respectively), annual unit rebuild cost (averaged over the 2-year period) results. These data are shown in Figure 4. This approach clearly identifies those equipment classes which show greatest potential for reduction in Air Force diesel engine maintenance expenditure. Correspondingly, the four significant classes (loading vehicles, fire trucks, construction vehicles, and facility equipment) would appear to be the most likely candidates for inclusion in any future Air Force OAP. Identification of potential engine problems by OAP methodology for these classes would seem to have the dual advantages of (a) reduction in Air Force maintenance cost and (b) reduced down-time for certain items of equipment which, although relatively small in number, are obviously critical to Air Force support operations.

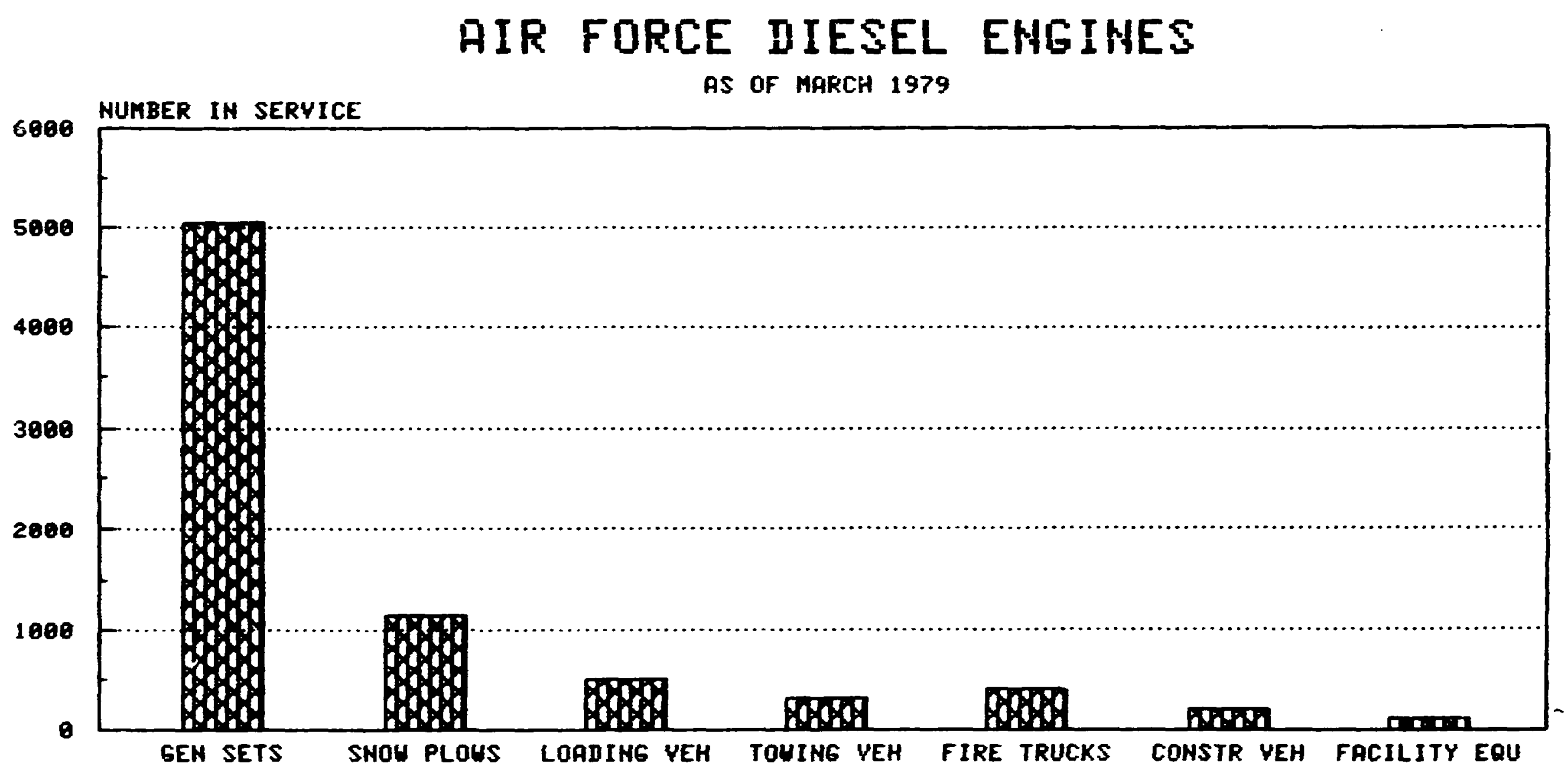

FIGURE 1. END ITEM INVENTORY BY EQUIPMENT TYPE

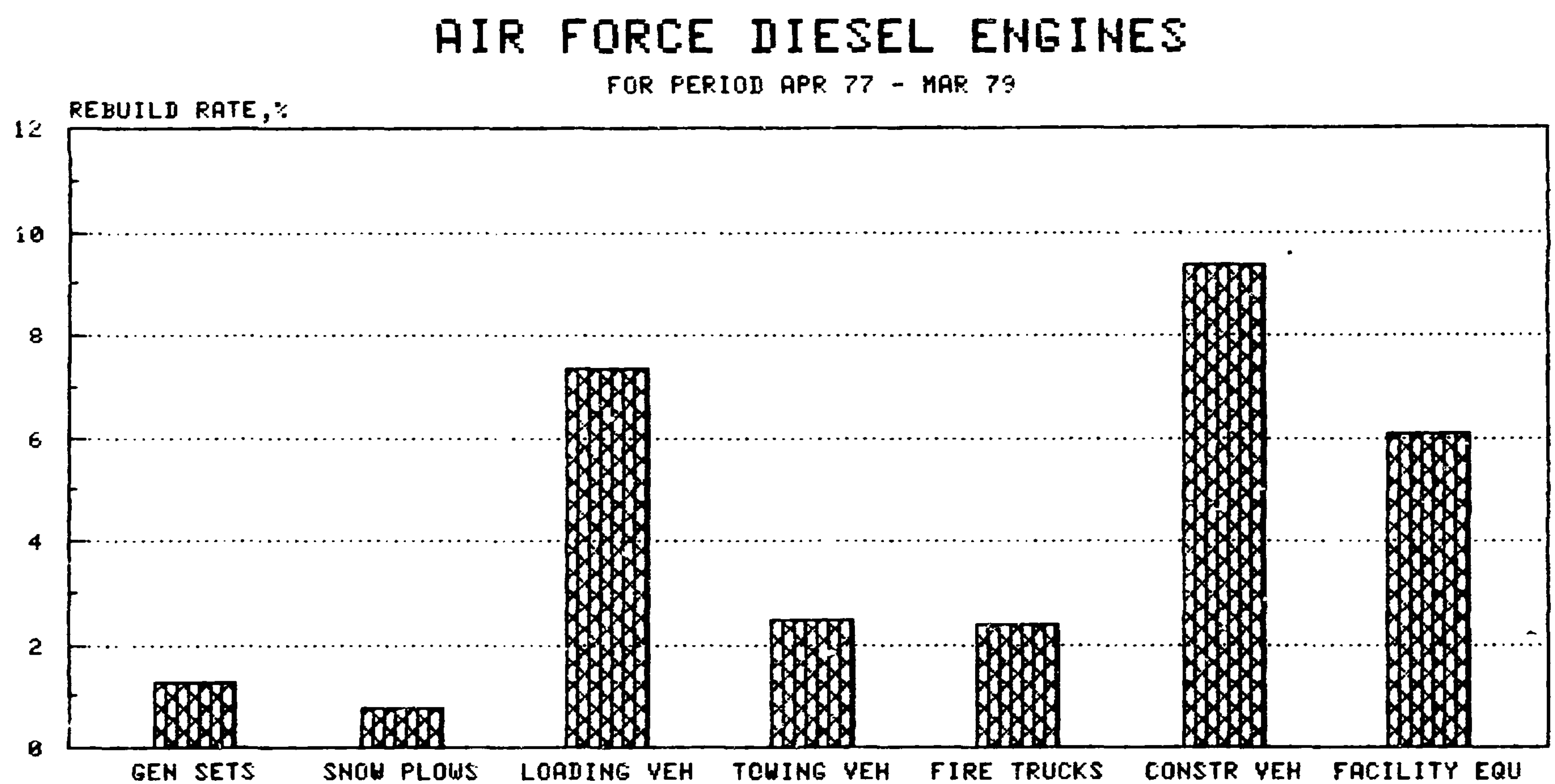

FIGURE 2. ANNUAL ENGINE REBUILD RATE BY EQUIPMENT TYPE

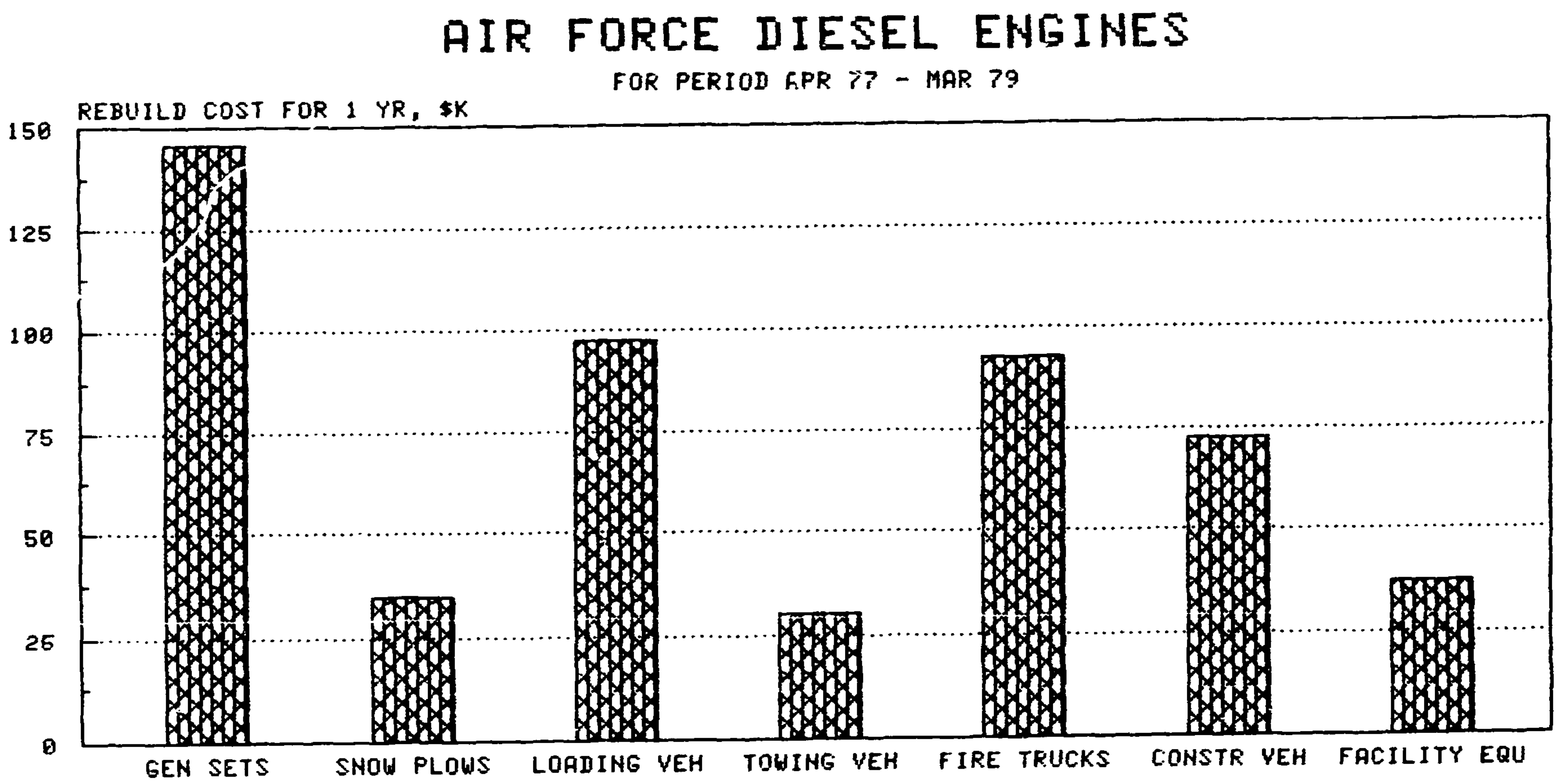

FIGURE 3. .NUAL REBUILD COST BY EQUIPMENT TYPE

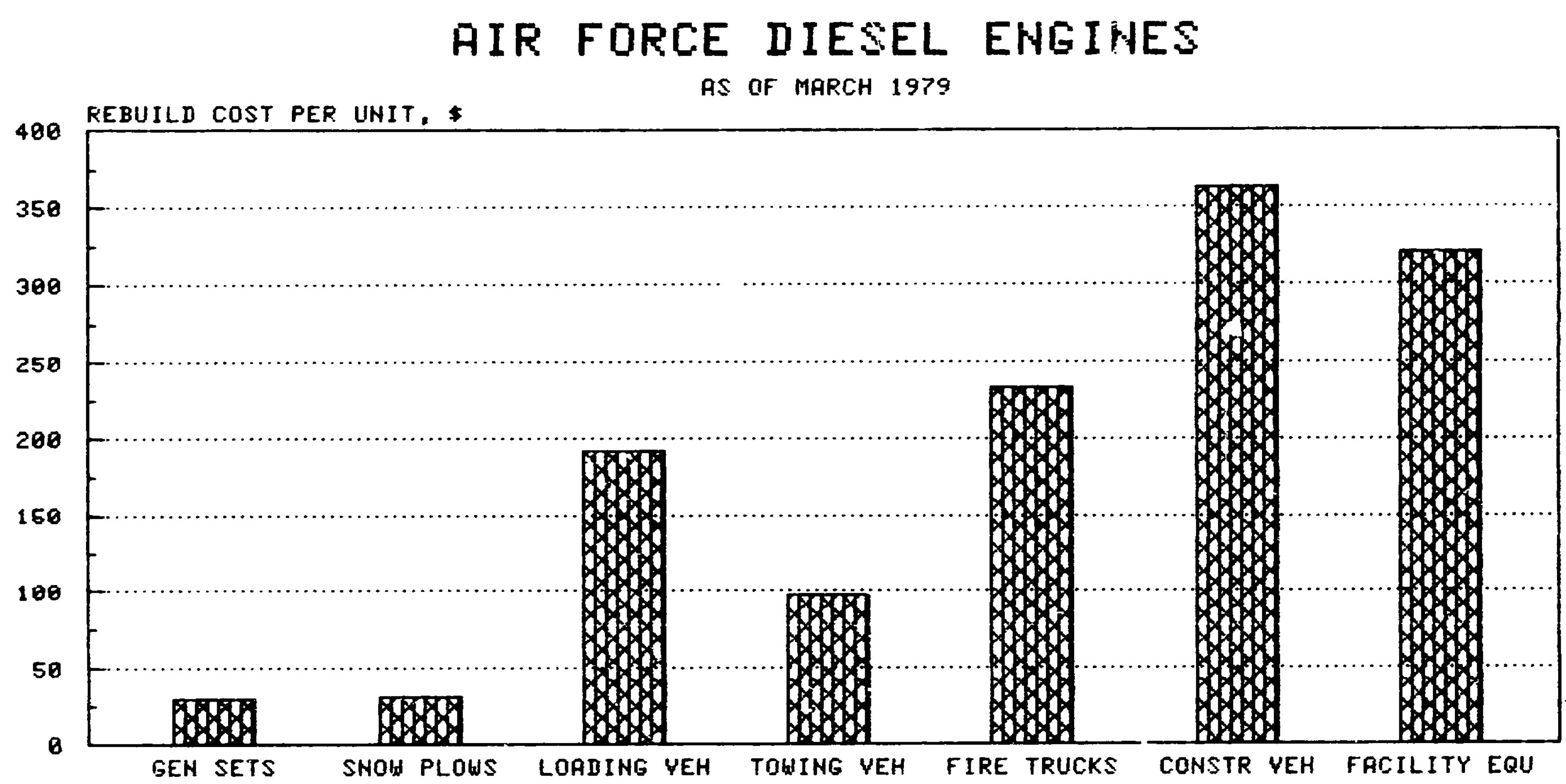

FIGURE 4. ANNUAL REBUILD CCST PER UNIT IN SERVICE

SECTION III
USED OIL ANALYSIS

General

This program task dealt with an evaluation of analytical techniques and sampling procedures applicable to diesel engines, for possible implementation by Air Force field-level personnel and OAP laboratories. The effort sought to compile and assess available background experience and data, both commercial and military. Lubricant analyses of interest were principally those capable of signaling incipient engine malfunction such that corrective maintenance actions can be recommended prior to the time of extensive mechanical damage. This category of determination basically includes spectrometric oil analysis for engine wearmetals and physico-chemical oil analyses for the presence of contaminants such as fuel, dirt, engine coolant, or other insolubles.

While not totally separable, analytical techniques indicative of lubricant integrity, such as oxidative deterioration or additive depletion, were of secondary importance. Emphasis was placed on those characteristics of the lubricant which might serve as criteria of engine performance, as opposed to those which might indicate the need for oil change.

Through correspondence, telephone contact, and personal interviews, currently recommended practices related to diesel engine oil analysis were determined for several analytical service laboratories, military agencies, major oil suppliers, and engine manufacturers. Personnel were asked to describe the type and purpose of analyses performed for their customers, as well as limit criteria. Varied responses were given in regard to the latter. Some laboratories had established limit criteria available, others applied criteria promulgated by their customers, while some stated that decisions were based solely on trend analysis without regard to specific limits.

Analytical Services

Commercial Analytical Services. Analysts, Inc. serves a large number of commercial diesel engine operators. This company performs a spectrometric analysis of oil samples to determine wear, the presence of coolant (coolant additives), dirt (indicative of air intake problems), and lubricant identification (additive metals). The following listing identifies element types and possible sources:

<u>Wearmetals</u>
Iron
Lead
Copper
Chromium
Aluminum
Nickel
Silver
Tin

<u>Coolant Additives</u>
Boron
Sodium

<u>Lubricant Additives</u>
Phosphorous
Zinc
Calcium
Barium
Magnesium

<u>Dirt Ingestion</u>
Silicon

Analysts, Inc. does not advocate the application of wearmetal limits, preferring to base recommendations on the rate of change in concentration. Standard physico-chemical testing includes fuel dilution, total solids, water content, Saybolt viscosity at 210°F, and total base number.

Analysts, Inc. instructs its customers to collect samples after the equipment has been in operation for at least 15 minutes and while still warm. Recommended sampling points, in order of preference, are a petcock installed in the oil line before the filter, the oil dipstick tube, and the lubricant sump drain.

The Technical Service Laboratories of Mobil Oil Corporation offer a commercial service for the monitoring of diesel engines. They perform a wearmetals analysis by emission spectrometer. Lubricant analyses conducted by Mobil include automated Brookfield viscosity, membrane filtration in pentane for insolubles, and differential infrared analysis for water (at 2.9 micrometers), glycol (at 9.3 and 9.7 micrometers), and oxidation (at 5.8 micrometers). Fuel dilution is estimated from viscosity data. Table 3 illustrates the wearmetal criteria developed by Mobil while Table 4 presents their interpretation of oil analysis data.

TABLE 3. TYPICAL DIESEL ENGINE WEARMETAL CONTROL LIMITS
(Mobil Technical Service Labs)

	Engine Classification			
	2-Cycle		4-Cycle	
Metals, ppm	Moderate Volume Displacement	High Volume Displacement	Moderate Output Engines	Higher Output Engines
Silicon	16–20	9–12	16–20	16–20
Iron	71–100	61–80	71–100	161–190
Aluminum	8–15	8–15	16–20	16–20
Copper	26–40	61–80	16–50*	36–55
Lead	21–40	21–40	24–50*	51–70
Tin	6–15	6–15	6–16	6–15
Chromium	11–15	6–10	11–15	16–20
Boron**	21–40	21–40	21–40	21–40

Note: All ranges shown above are considered the borderline region. Below this range, results are satisfactory; above it, results are unsatisfactory.

* Maximum value may be reduced in certain critical engines.
** Boron may be present as an oil additive. If so, boron is less useful in coolant leak determinations.

TABLE 4. INTERPRETATION OF ANALYTICAL RESULTS
(Mobil Technical Service Labs)

Lubricant API Classification - CD/SE

SAE Viscosity Grade:	10	20	30	Higher Output Engines 30	40	50
Viscosity Controls*						
Min	−3	−5	−8	−8	−10	−18
Max	+8	+7	+8	+10	+7	+12
Fuel Dilution, % est (B)	5	5	5	5	5	5
Water, wt% (B)	- - - - - - 0.15–0.20 - - - - - - - -					
Glycol, wt% (U)	- - - - -Any Detectable Amount- - - -					
Oxidation, A/cm (B)	20–25	20–25	20–25	25–30	20–25	20–25
Insolubles, wt%, 0.3 μm (B)	- - - - - - 3.5–4.0 - - - - - - - - -					

B = Borderline
U = Unsatisfactory
* Normal or satisfactory for SUS change from average new oil viscosity.

Optimal Systems, Inc. performs a spectrographic oil analysis for diesel engine wearmetals. Elements recorded are those cited by Analysts, Inc. plus molybdenum. The normal test methods additionally used by Optimal include 210°F kinematic viscosity and differential infrared spectroscopy. The latter serves to identify water, oil oxidation products, nitration, ethylene glycol, fuel dilution, and soot. A rapid gas chromatography technique may also be used for a determination of fuel in the lubricant.

Cleveland Technical Center, Inc. offers its "Spectra-Check" services for preventive maintenance. The recommended tests for diesel engine monitoring include analysis for 18 elements (those listed for Analysts, Inc. plus antimony and manganese) by emission spectrometer. Fuel dilution in the lubricant is estimated from the flash point of the oil performed by ASTM Method D 92. Water and insolubles are determined by centrifuge per Method D 96. Lubricant Saybolt viscosity is evaluated at 100°F. A blotter spot technique is utilized for indication of adequate oil detergency.

A number of comments pertinent to diesel engine surveillance were offered during a panel presentation on "Oil Analysis--A Predictive Maintenance Tool" held at the Energy Technology Conference and Exhibit in Houston, Texas, 8-9 November 1979.

Southwest Spectro-Chem Laboratories, Inc. described its service available in this area. This company employs emission spectroscopy for 16 elements (presumably the same as those identified by Analysts, Inc.). Differential infrared is used to determine lubricant nitration and oxidation. Additional tests include viscosity and acid number. A blotter spot test technique is employed as a screening tool for insolubles, fuel dilution, and the dispersancy effectiveness of the oil.

A representative of Union Carbide described the analyses conducted by a commercial laboratory (unidentified) for his firm. Sixteen elements are determined spectroscopically. Testing is also performed to determine viscosity, acid number, water, and blotter spotting. Infrared is available, but it is not routinely used. Unlike the recommendations of others, Union Carbide prefers a selected oil sampling point downstream of the oil filter for sampling valve location.

In-House. On-site interviews were conducted at the oil analysis laboratory of H.B. Zachry Company. Zachry is a large construction firm engaged in international operations. Its laboratory analyzes some 30,000 samples per year and monitors both diesel and gasoline engines. Emission spectroscopy is used to determine the concentration of 22 elements in used oil samples. Flash point and viscosity data are used as indicators of fuel dilution, oil oxidation, or high particulate levels. Lubricant systems are sampled at the time of oil change (150 hours).

Zachry is presently implementing a totally automated data system. Its goal in oil analysis is the development of rapid test techniques for wearmetals, viscosity, fuel dilution, etc., requiring a total analysis time of 3 minutes or less.

Military. Contact and discussions were initiated with various personnel involved in military oil analysis studies or programs for nonaeronautical equipment. Facilities included the Long Beach Naval Shipyard, the tri-service's Joint Oil Analysis Program Technical Support Center (JOAP-TSC) at Pensacola, Florida, and the Army's Materiel Readiness Support Activity (MRSA) at Lexington, Kentucky.

Oil analysis work at Long Beach has a limited scope. Samples are taken from test-cell runs on rebuilt diesel engines. Trend analysis is employed in monitoring wearmetal concentrations, primarily for iron, aluminum, silver, lead, zinc, tin, and copper. Criteria have been developed through experience and would probably not be applicable to field service.

Discussions with JOAP-TSC representatives were held on 1 December 1978 during a visit to SwRI. Their recommendations pertained to the use of modified methods for lubricant property assessment. The following procedures were noted:

- Insolubles -- by centrifuge using heptane with a coagulant

- Viscosity -- by vibrating sphere procedure (Nametre viscometer)

- Fuel dilution -- low-resolution gas chromatography

- Soot and oxidation -- blotter spot test and infrared spectrometer.

MRSA at Lexington has primary responsiblity for the Army Oil Analysis Program (AOAP). Initially, AOAP was restricted to wearmetal surveillance for aircraft. In recent years, the program was expanded to include nonaeronautical equipment. More recently, physico-chemical testing has been added for the latter equipment, principally diesel-engine-powered vehicles. Reduced maintenance costs and extended oil change intervals are AOAP goals, and data for 1978 showed an impressive 20 to 1 cost savings for the overall program (aero and nonaero equipment).

For nonaeronautical equipment on normal oil change intervals, AOAP proposes use of the following tests:

- Emission spectroscopy for 20 elements
- Blotter spot test for solids
- Crackle test (hot-plate) for water
- Nametre technique for viscosity
- Centrifugation for solids (required only for positive indication by blotter spot, crackle test, or viscosity increase)
- Gas chromatography for fuel dilution (required only for indication of reduced viscosity or sample burning during spectrometric analysis).

Acid and base number titrations are added to the above list for equipment on extended oil drain intervals.

Wearmetals criteria for several items of equipment have been promulgated by issuance of the AOAP Laboratory Guide for Nonaeronautical Equipment. This document has been scheduled for expansion to include additional items of equipment as well as lubricant property guidelines. The expanded version will be issued as a formal Army Technical Manual.

Analytical Practices

Major Oil Suppliers. The analytical practices of the major oil suppliers are discussed in the following paragraphs.

Texaco places emphasis on used oil analysis for two reasons: (1) to indicate used lubricant quality and (2) to disclose operational problems. Texaco's analysis program includes most of the standard procedures used by most analytical laboratories, including water content, viscosity, flash point, insolubles, neutralization number, blotter tests, ash content, and spectrographic analysis for metals content. The publication describing each of these tests also includes precautionary statements which essentially established the limiting values for the test results.

Table 5 describes the relationships between the used oil analysis to engine condition or operation parameter.

Spectrographic analysis is also used to establish the concentration of various metals in the used oil. The metal concentrations of the new oil are compared to the concentration of metals in the used oil in order to establish engine wear and contamination levels.

Shell Oil also recommends a used oil analyses program, primarily to establish lube oil drain periods. The limits vary with engine types and service. Table 6 lists the conditions that are evaluated and general limits they have established. Shell Oil has also derived equations showing wear rate curves over extended usage. The equations also take into consideration the oil consumption for the particular engine. The results that Shell has obtained indicate that the rate of increase of certain contaminants is more important than the actual level that is determined.

Sun Oil does not normally conduct routine maintenance analyses of used lubricants to monitor equipment condition. However, for diesel lubrication studies, the following standard test procedures are used--kinematic viscosity, metals by emission spectrography, infrared, acid and base number, and glycol content. Sun Oil also recommends some type of di-electric measurement as a quick and cheap indicator of more serious problems.

TABLE 5. RELATION OF USED CRANKCASE OIL ANALYSIS TO ENGINE CONDITION OR OPERATION

Test Result	Probable Cause	Contributing Engine Condition or Operation
Water contamination	1. Condensation	Low-temperature operation Low-cooling jacket temperature Inadequate crankcase ventilation Excessive engine idling Short periods of intermittent service
	2. High blowby	Ring belt area Worn rings or liners Stuck or broken rings Exhaust system restrictions
	3. Coolant leakage	Leaking head gasket Improperly torqued cylinder head Defective or blown gasket Leaking seals on wet-side liners Defective seal Improper installation Cracked block or cylinder block
Viscosity reduction	1. Use of lower viscosity product	---
	2. Fuel dilution	Overfueling Restricted fuel return line Oversize injectors Poor combustion Poor injector spray pattern Dribbling injectors Restricted air supply or exhaust system Worn rings and liners Ring sticking or breakage
Viscosity increase	1. Use of a higher viscosity product	---
	2. Contamination	Water Fuel soot--discussed under insolubles

TABLE 5. RELATION OF USED CRANKCASE OIL ANALYSIS TO ENGINE CONDITION OR OPERATION (Cont'd)

Test Result	Probable Cause	Contributing Engine Condition or Operation
	3. Degradation	High-temperature operation Peak power output Inadequate cooling Lean operation Over-extended oil drains
Insolubles contamination	1. Fuel soot	Rich operation Overfueling Restricted air intake Defective injectors Poor spray pattern Dribbling nozzles Worn rings or liners, stuck rings
	2. Ingested dirt	Inadequate air filter maintenance Air leaks in intake system
	3. Wearmetal	Generally related to quantity of ingested dirt Inadequate oil filter maintenance
	4. Oil degradation	High-temperature operation Overextended oil drains Oil pumping Worn bearings, valves, guides and rings High crankcase oil level
Neutralization number		
Slow or moderate rise	Effects of normal service	---
Rapid rise	1. Contamination	Fuel blowby products
	2. Oil oxidation	Excessive operating temperatures Overextended service period
Strong acids present	Heavy fuel blowby	Low-cylinder wall temperatures Inadequate water washing during purification
Total base number		
Slow reduction	Effects of normal service	---
Rapid reduction	Heavy fuel blowby	---

TABLE 5. RELATION OF USED CRANKCASE OIL ANALYSIS TO ENGINE CONDITION OR OPERATION (Cont'd)

Test Result	Probable Cause	Contributing Engine Condition or Operation
Differential infrared increased absorption at 5.8-5.9 micrometers		
Slow rise	Effects of normal service	---
Rapid rise	Oil oxidation	Overextended service High-temperature oxidation High piston and cylinder temperatures Engine hot spots High bulk oil temperature
Increased absorption at 6.2 micrometers	Nitrogen fixation	Lean fuel-air ratios Faulty crankcase ventilation Excessive blowby Engine overload
Reduced ash content	1. Use of low ash product	---
	2. Additive loss	Degradation due to severe service Water contamination and sludging Use of active clay filters that remove additives
Increase ash content	1. Use of higher ash product	---
	2. Contamination	Ingested dirt Engine metal wear Cylinder oil residues

TABLE 6. RECOMMENDED USED OIL ANALYSES PROGRAM

Condition	Laboratory Tests	General Condemnation Limits
1. Coolant leak	Water content, vol%	0.2 max
	Glycol content, vol%	present
	Boron, ppm	(a)
	Sodium, ppm	(a)
	Silicon, ppm	(a)
	Shell ADC oil spot test	(b)
2. Fuel leak	Fuel dilution, vol%	5.0 max
	Viscosity change at 210°F, %	-15 min
3. Air filtration	Silicon, ppm	20 max
4. Lube oil oxidation	Viscosity change at 210°F, %	+20 max
	Differential IR analysis at 5.8 micrometers	(c)
5. Suspended solids	Pentane and benzene insols., wt%	(c)
	Shell ADC oil spot test	(b)
6. Alkalinity	TBN-E (D 664)	0.5 min
	TAN-E (D 664)	6.0 max
	Initial pH	4.5 min
	Shell ADC oil spot v/color indicator	color change
7. Engine wear	Metal content, ppm	
Cylinder liners,	Fe	(c)
rings, etc	Cr	(c)
Bearings	Pb	(c)
	Cu	(c)
	Al	(c)
8. Screening tests	Shell OCI meter	(c)
	Hopkins An-oil-izer	(c)

(a) Limit dependent on concentration of element present in new oil and coolant.
(b) Impaired dispersance pattern.
(c) Limit varies with engine type and service.

Conoco considers that there are, basically, two oil-degrading conditions within the diesel engine. These two conditions are temperature and contamination, and, in effect, cause both chemical and physical changes in the performance of the lubricant. Conoco recommends and routinely conducts tests to evaluate the effects of these two conditions. These analyses include kinematic viscosity, flash and fire point, fuel dilution, coagulated insolubles, particulate content, acid number, infrared analysis, and emission spectrographic analysis for metals content.

Conoco states that it considers viscosity as the most significant property since it is of direct functional importance. If the viscosity is too low, the lubricant allows excessive blowby and permits wear; if the viscosity is too high, the oil will not lubricate properly. Factors affecting viscosity changes are oxy-polymerized products, glycol and water contamination, fuel and soot contamination, and nitration products. Conoco analyses have shown that flash point is a good indicator of fuel dilution, except where oxidation has occurred or where soot is present.

Chevron Research has an active program to analyze used oil samples to determine the quality of the remaining lubricant. Its tests are conducted to determine when the lubricant is contaminated and when the lubricant changes physically and chemically. Table 7 shows the changes in which Chevron is interested, and Table 8 shows the test methods used to determine these changes. The Chevron Research approach is to conduct the basic tests. Then, if results that are out of specification limits are obtained, supplementary tests are performed.

Engine Manufacturers. The analytical practices of five of the major engine manufacturers are discussed in the following paragraphs.

Teledyne Continental Motors (TCM). Listed in Table 9 are the analytical procedures conducted by TCM on the lubricants of interest. It is noted that the procedures apply to lubricant monitoring for production and developmental test stand engines being run at TCM. The company does not presently recommend an oil analysis program for their customers because it is felt that additional work is needed to establish the value of such programs. TCM is

TABLE 7. FACTORS CAUSING CHANGES IN LUBRICANT SERVICE LIFE

Causes	Appearance and Odor	Crackle Test	Blotter Spot Test	Viscosity	Spectro Analysis	Fuel Flash Point	Dilution (Measured)	Water Content	Glycol Test	Insolubles	Alkaline Reserve	Infrared Analysis
Contamination												
Fuel Combustion Products	X		X	X						X	X	X
Liquid Fuel	X			X		X	X					X
Wear Metals	X				X					X		
Dirt	X				X					X		X
Water	X	X	X					X				X
Coolant Additives					X				X			
Breakdown												
Oxidation and Nitration	X		X	X						X	X	X
Loss of Additive Effectiveness			X							X	X	X
Viscosity Loss (Multigrade Oils)	X			X								

TABLE 8. ASTM STANDARD METHODS OF TEST USED BY CHEVRON FOR ENGINE LUBRICATING OILS

Common Name	ASTM Designation[a]	ASTM Name (Standard Method of Test for:)
Gravity or Density[b]	D 287	API Gravity of Crude Petroleum and Petroleum Products (Hydrometer Method)
Color[b]	D 1500	ASTM Color of Petroleum Products (ASTM Color Scale)
Carbon Residue[b]	D 189	Conradson Carbon Residue of Petroleum Products
Flash and Fire Points (Cleveland Open Cup--COC)	D 92	Flash and Fire Points by Cleveland Open Cup
Flash Point (Closed Cup)	D 93	Flash Point by Pensky-Martens Closed Tester
Pour Point	D 97	Pour Point
Viscosity (Centistokes)	D 445	Viscosity of Transparent and Opaque Liquids (Kinematic and Dynamic Viscosities)
Viscosity Index[b]	D 2270	Calculating Viscosity Index From Kinematic Viscosity
Viscosity Conversion	D 2161	Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity
Viscosity-Temperature Charts	D 341	Standard Viscosity-Temperature Charts for Liquid Petroleum Products
Fuel Dilution	D 322	Dilution of Gasoline-Engine Crankcase Oils
Water	D 95	Water in Petroleum and Other Bituminous Materials
Foaming Tendency	D 892	Foaming Characteristics of Lubricating Oils
Insolubles	D 893	Insolubles in Used Lubricating Oils
Precipitation Number	D 91	Precipitation Number of Lubricating Oils
Trace Sediment	D 2273	Trace Sediment in Lubricating Oils
Acid Number (TAN or TAN), Base Number (TBN or TBN), pH	D 664	Neutralization Number by Potentiometric Titration
TBN by Perchloric Acid Method or Alkalinity Value	D 2896	Total Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration
TAN, SAN, TBN (Colorimetric)	D 974	Neutralization Number by Color Indicator Titration
Ash[b]	D 482	Ash From Petroleum Products
Ash (Sulfated)	D 874	Sulfated Ash From Lubricating Oil and Additives
Metals[b]	D 811	Chemical Analysis for Metals in New and Used Lubricating Oils
Phosphorus[b]	D 1091	Phosphorus in Lubricating Oils and Additives
Sodium[b,c]	D 1026	Sodium in Lubricating Oils and Additives (Gravimetric Method)
Sulfur[b,c]	D 1552	Sulfur in Petroleum Products (High-Temperature Method)

(a) These numbers may be followed by a dash (--) and other numbers or letter which indicate year of issue, revision, and/or adoption.
(b) Used primarily for fresh oils or additives.
(c) Sulfur can also be measured by other methods including D 129, D 1551, or D 2622.

TABLE 9. TESTS CONDUCTED BY TELEDYNE CONTINENTAL ON LUBRICANT SAMPLES

Test	#1	#2	#3	#4
Kin. Viscosity				
at 100°F	X	X	X	X
at 210°F	X	X	X	X
Viscosity Index	X	X	X	X
Total Base No.	X	X	X	X
Pentane Insolubles	X		X	X
Benzene Insolubles	X		X	X
Insoluble Resins	X		X	X
% Water by Infrared	X	X		X
IR Trace		X	X	X
Flash Point	X	X	X	X
Specific Gravity	X	X	X	X
Wearmetals				
Iron	X		X	X
Chromium	X		X	X
Aluminum	X		X	X
Silicon	X		X	X
Nickel	X		X	X
Lead	X		X	X
Copper	X		X	X
Zinc	X	X	X	X
Calcium	X	X	X	X

#1 = 50-hr endurance engine - monthly
#2 = New oil--all bulk shipments
#3 = 400-hr endurance engine
#4 = Failed engine analysis

In TCM's production test cells, the oil is changed every 45 days, or 200 hours of cell operation, whichever comes first. At approximately 22 days or 100 hours of cell operation, an oil sample is taken, and the water content, specific gravity, and sediment (pentane, benzene, and resin insolubles) are checked.

currently investigating some aspects of oil condition monitoring, e.g., they are conducting tests to determine the correlation between test dust additions to the lubricant and engine damage, versus spectrometric determination for silicon.

General Motors (GM). GM does not include any statement in their owner manuals regarding used oil analysis as a guide to preventative maintenance. The reason given by GM's Research Laboratories is that oil type/quality, type of service, and vehicle condition vary considerably. GM feels that it is not possible to assess the significance of results encompassing all of these variations. GM feels that oil analysis techniques for preventative maintenance are useful only in "closed-loop" operations in which equipment, materials, maintenance, and use are essentially identical. Furthermore, even with the aforementioned parameters held constant, used oil analyses only provide a means to detect an abnormal change when compared against established baselines.

GM has established both normal and severe service oil change recommendations. These recommendations are based on the results obtained from a number of field tests which include general transportation, proving ground, short-trip, taxi, police fleet, etc. In their studies they utilize many oil analyses techniques to determine the oil condition. These tests include viscosity measurements, TAN and TBN measurements, insolubles, water and fuel dilution, metals content, carbonyl and other infrared characteristics, and carbon content.

Caterpillar Tractor Company. The Caterpillar Tractor Company Scheduled Oil Sampling Program has been in use since 1970 and has been described in a paper, "Scheduled Oil Sampling as a Maintenance Tool," SAE Paper No. 72 0372 authored by R.L. Klug. Nine metals (Pb, Mo, Mg, Na, Fe, Cu, Cr, Al, and Si) in addition to fuel dilution (by flash point), antifreeze and water detection are routinely determined. Products of wear can indicate mechanical condition and eliminate premature overhaul. Testing is done by any Caterpillar dealers who also interpret the results and make recommendations to the customer.

Cummins Engine Company. Cummins does not encourage the general use of used oil analyses as a preventative maintenance tool or as a method to determine oil change intervals. Table 10 lists the tests that are conducted in field test programs and indicates the limiting values. Spectrographic analysis of wearmetals is not included since prediction of engine failure has been only marginal (versus cost) at best.

Detroit Diesel Allison (DDA). This company publishes a guide establishing the lubricant quality to be used in their engines. DDA requires an SAE 30 or 40 weight oil or a multiviscosity 15W-40. DDA states that oil change intervals depend upon operating conditions and sulfur content of the fuel. The following conditions provide warning values requiring a change of lubricant and/or corrective maintenance action:

(1) The presence of ethylene glycol
(2) Fuel dilution exceeding 2.5% (vol)
(3) Viscosity increase greater than 40% over the new oil (vis at 100°F)
(4) Iron content greater than 150 ppm
(5) Coagulated pentane insolubles exceeding 1 wt%
(6) Total base number lower than 1.0 (ASTM D 664)

As a general rule, DDA indicates that operating conditions vary, even with comparable mileage or hours. Therefore, maintenance schedules should vary.

Summary

Tables 11 and 12 list the various test techniques utilized by the several organizations contacted in this task. It should be noted that test assignment for an individual laboratory is made only for a specific property determination, e.g., centrifugation for total solids. Similarly, some labs do not perform a specific test for fuel dilution, but will utilize viscosity data for this purpose.

As seen in Tables 11 and 12, most organizations listed perform a spectrometric analysis for wearmetals, lubricant or coolant additive elements, and silicon. All labs conduct some type of lubricant viscosity determination. This lubricant measurement serves a multitude of purposes.

TABLE 10. ANALYTICAL PROCEDURES USED BY CUMMINS ENGINE COMPANY (Including Limiting Values)

Property	Test Method	Test Limits
Viscosity at 40° and 100°C	D 445	+ 1 SAE Grade or reduction approx equivalent to 5% fuel dilution or 10% increase at 100°C or 25% increase at 40°C
Insolubles, n-pentane	D 893	1.5% max
Insolubles, benzene	D 893	1.0% max
Total Acid Number	D 664	3.5 number increase above new oil value
Total Base Number	D 664	2.0 min
Water Content	D 95	0.5% max
Additive Reduction	AES or AAS	25% max

TABLE 11. TEST TECHNIQUES FOR DIESEL ENGINE MONITORING - SERVICE LABS

Organization	Spectrometric Analysis	Saybolt Viscosity	Kinematic Viscosity	Absolute Viscosity	Nametre Viscosity	Fuel Dilution	Solids	Water	Acid No.	Base No.	Blotter Spot	Infrared Spectroscopy
Analysts, Inc.	X	X				X	X	X		X		X
Mobil Tech Svc	X			X		X	X					X
Optimal Systems	X		X			X	X	X			X	
Cleveland Tech	X	X							X		X	X
SW Spectro-Chem	X		X					X	X		X	
Union Carbide Svc	X	X				X						
H.B. Zachry	X	X			X	X	X	X	X*	X*	X	
AOAP	X											

* Only for extended oil drain applications.

TABLE 12. TEST TECHNIQUES FOR DIESEL ENGINE MONITORING--OIL COMPANIES AND ENGINE SUPPLIERS

	Texaco	Shell	Sun Oil	Mobil Oil	Conoco Oil	Chevron Oil	Teledyne Continental	General Motors	Caterpillar Tractor	Cummins	Detroit Diesel
Viscosity											
at 100°F D 445	X		X	X	X	X	X	X		X	X
at 210°F D 445	X	X	X		X	X	X	X		X	
VI	X					X	X				
TBN D 974 & D 664	X	X	X		X	X	X	X		X	X
TAN	X	X	X		X	X		X		X	
Pentane Insol. D 91	X	X		X			X	X		X	
Benzene Insol.	X									X	
Coag. Insol.		X			X					X	
Water -IR				X			X	X			
Water D 95	X	X				X				X	
Glycol D 2982		X	X						X		X
Oxidation	X	X	X	X	X	X	X	X			
Nitration											
Flash Point D 92, D 93	X				X		X		X		
Fire Point	X				X		X				
Metals Spectro	X	X	X	X	X	X	X	X	X		X
Blotter	X					X					
Ash	X										
Fuel Dilution		X		X	X	X		X			X
Millipore Filtration Particles				X							
H_2O Crackle						X			X		

A significant viscosity decrease may indicate fuel dilution or oil makeup using an improper (lower) lubricant grade. An appreciable viscosity increase could signal the use of an improper (higher) lubricant grade, the presence of excessive contaminants, or oxidative thickening.

While the test techniques vary, most organizations listed in Tables 11 and 12 concur with respect to the importance of evaluating lubricants for the presence of fuel, water, and solids. Several employ the blotter spot test as a preliminary indication of such contamination. Acid and base number determinations are employed infrequently on a routine basis.

Infrared spectroscopy is a versatile tool used by three labs. However, the technique requires relatively expensive instrumentation and a trained interpreter. Further, there are difficulties encountered in the application of infrared to equipment in which lubricants from several suppliers may be commingled, as is the case in the military services.

State-of-the-Art

In support of the survey of oil analysis techniques and procedures, a brief literature search was conducted on the state-of-the-art in oil analysis. A description of this search and results therefrom are presented in the Appendix of this report.

Technical Evaluation

Of the ten responses received from lubricant suppliers and engine manufacturers, there was some conflict of opinion with regard to the usefulness of oil analysis programs for diesel engines. One of five lubricant suppliers felt that such programs were of value only for closely controlled developmental studies. Two of five engine manufacturers expressed similar opinions, while a third suggested that additional study is required to establish the value of oil analysis relative to maintenance savings. All other engine and lubricant company respondents appear to be convinced of the applicability of oil analysis and are actively promoting its implementation. Within this group are two of the largest diesel engine manufacturers in the industry. A similar view is apparently held by the Army which is planning to expand the AOAP coverage to include 2-1/2 ton and larger wheeled vehicles, 15 kW and larger generator sets, materiel handling equipment over 4000 lb, and other equipment.

Definitive studies were not available which make it possible to select with certainty between the opposing viewpoints as to the value of oil analysis. Obviously, if definitive studies and findings were available, there would be a unanimity of opinion, either pro or con. Virtually all of the lubricant suppliers and engine manufacturers contacted agree that oil analysis is useful in cases in which materials, equipment, and conditions of operation are essentially identical. While this requirement certainly serves to simplify the interpretation of analytical results, it is not felt that any deviation from such conditions precludes the use of oil analysis for monitoring engine condition. It was also indicated that used oil analysis can be effective in situations involving poor maintenance practices.

Intuitively and scientifically, it is believed that the applicability of spectrometric wearmetal analysis for the detection of certain types of incipient mechanical failure has been adequately demonstrated for selected internal combustion engines. A change in the severity of equipment operation can obscure wear trends but, with experience, the laboratory evaluator can apply judgmental corrections in such cases, or obtain information from the user which will permit an accurate assessment of the circumstances.

There is no doubt that excessive oil degradation or contamination by fuel, water/coolant, soot, dust/dirt, or oxidation will impair the lubricant's function and may result in engine distress. Because of the complexity of operation and the numerous interrelated factors involved, it is difficult to establish a strict correlation between, say, fuel dilution and crankshaft bearing wear. Nevertheless, it is apparent that any significant changes in the physical-chemical properties of a lubricant compounded for a specific application is potentially harmful to the lubricated mechanical system, and early detection of any such change may minimize or eliminate the potential distress. Thus, the question as to the pertinence of an oil analysis program is believed answerable primarily on the basis of economic considerations. This subject is addressed in Section IV of this report.

Various general and specific limits on used oil properties were cited by the several respondents. With respect to wearmetal concentration limits, virtually all respondents stated that these criteria vary with engine type and service and, as a consequence, wearmetal limits must be established on the basis of user experience. This approach is believed to be particularly applicable to any proposed Air Force program. Thus, wearmetal guidelines should be developed through a statistical analysis of sample data, and a diagnostic capability developed through guidance obtained from engine manufacturers and/or maintenance feedback information.

Several respondents cited specific limits for lubricant properties such as percent viscosity change, percent fuel dilution, water content, etc. The limits given, however, were not totally consistent and no basis for selecting a particular value was provided. Here again, engine tolerance to a lubricant property change would be expected to vary depending on engine type and service. It is believed that property limits proposed by the respondents are sufficiently consistent to permit selection of tentative criteria, e.g., by specifying the most restrictive values.

In evaluating the various test procedures/methods in use for diesel engine oil analysis, several criteria were considered. These criteria included applicability for the oil property of interest, simplicity, rapidity, cost, and suitability for use at Air Force OAP laboratories. Many of the tests are standardized ASTM (American Society for Testing and Materials) procedures with established values for repeatability and reproducibility. Two nonstandard procedures, the blotter spot test and the crackle test, are somewhat subjective in interpretation and provide only qualitative information.

Spectrometric analysis for wearmetals and other elements of interest is an established procedure, and this capability presently exists in the Air Force OAP laboratories. Oil viscosity is considered a most critical property since any appreciable change in its value will result in a loss of the load-carrying or lubricating ability of the fluid. Numerous reliable, standardized methods are in use for viscosity measurement; many are directly related, others are related through a lubricant density factor. The choice of an appropriate technique is, therefore, dictated by the elements of equipment cost and ease of performance. In the subsequent analysis of program economics, the use of a vibrating sphere technique for viscosity determination is proposed. While the apparatus is relatively expensive compared to alternate methods, the procedure is extremely rapid and easy to perform. It is believed these advantages overbalance the disadvantage of high equipment cost, especially for a program with the potential for high-volume analyses.

Other test techniques cited in this section such as neutralization number, infrared spectroscopy, benzene/pentane insolubles, etc., are certainly appropriate for their intended application, but are primarily associated with the goal of extended lubricant drain periods. Such test methods are also relatively complex in performance and interpretation. In addition to spectrometric analysis and viscosity measurement, three additional procedures are considered on the basis of economy, simplicity, and speed of performance. These are the crackle test for excess water, the blotter spot test for soot and dispersancy characteristics, and pH determination for acid or alkalinity change. In combination, it is felt that these five techniques provide the optimum information for diagnosis of engine operation as reflected by lubricant change or contamination, while also meeting many of the test evaluation criteria previously listed.

As noted earlier, the crackle test and blotter spot test are somewhat subjective and will require an accumulation of experience for proper use by laboratory personnel. It is believed that the AOAP laboratories use the crackle (hot-plate) test principally as a gross indication of excess water. One description (reference 22 in the Appendix) of the test calls for the use of oil standards containing 1 percent, 0.1 percent, and a "trace" of free water, at a hot-plate temperature of 230°F. Assuming the technique is sensitive to the presence of 0.1 percent water, the method would provide for detection below the various limits offered by some respondents. In the case of the blotter spot test, interpretive aids in the form of photographic examples can be used to demonstrate excessive soot levels, impaired dispersancy, and, also, the presence of free water.

One category of lubricant test method which was not addressed in this study (primarily due to the lack of significant acceptance) was the instrumental technique for measurement of a change in electrical properties. Several commercial instruments are available which measure dielectric constant, or conductance or other electrical property of an oil. In most cases, the instruments are promoted as a "go-no go" prescreening tool which quickly and inexpensively provides an indication of the need for additional analysis. The value of a screening procedure of this type is apparent; however, further evaluation to establish the applicability of the various instruments is evidently required.

Recommended Analytical Techniques and Sampling Procedures

Based on a review of oil analysis service laboratories, used oil analytical practices by both lubricant and engine suppliers, and the assessment of the state-of-the-art in used oil analysis through a review of the literature as provided in the Appendix, the following recommendations have been deduced.

Sampling. Diesel engine oils are best sampled either by petcock-type valve installed in the pressurized oil gallery (preferred for highest quality oil sample obtained at lowest cost) or suction tube inserted via the dipstick tube into the oil reservoir. The oil should be sampled while still warm after the engine has been operated. Sampling from the bottom of the oil sump or the drain plug is not recommended since the sample may not be representative. The sampling operation is usually performed immediately prior to the actual draining of the oil. Oil additions during the drain interval or since the last sample submission should be recorded and reported, along with other information identifying the sample. Samples requested by the laboratory prior to oil drains should also be taken while the oil is warm and prior to makeup oil additions.

The rationale for hot versus cold oil sampling results from a consideration of the oil flow system and the physical properties of used oils. It is generally accepted that a hot engine oil has been well circulated throughout the oil system (galleries, pans, valve decks, etc.) by the very nature of the engine operation, which provides dynamic mixing of the oil. This mixing (attested to by the temperature of the sample) is required so that a representative sample is taken--a necessary requirement if representative analytical results are to be obtained. Typically, a used oil stratifies to varying degrees after engine shut-down and continued down-time; coincidentally, the oil cools to ambient temperature. Lubricant samples taken after prolonged engine shut-down are referred to as "cold samples" and are suspect as not being homogeneous, representative samples of the bulk oil. Consequently, analytical results for cold samples may not be representative and could lead to inaccurate interpretations of oil/engine condition.

Analytical Techniques. Engine condition is reflected by the engine oil due to three primary engine operating considerations:

- Wear
- Contamination
  - Fuel leaks (injector or lines)
  - Coolant
  - Dirt and dust ingestion
- Stoichiometry (air-fuel ratio)
  - Wrong or poor fuel (high sulfur)
  - Air intake or exhaust restrictions

Assuming proper lubricant and filter quality at proper change intervals, selected analytical techniques can detect abnormal oil properties reflected by engine component wear, contamination, or air-fuel stoichiometry. Analytical detection techniques include:

Analytical Technique	Source
• Metals	
• Fe	Component wear
• Pb	Component wear
• Cu	Component wear
• Cr	Component wear
• Ni	Component wear
• Al	Component wear or contamination
• Ag	Component wear
• Sn	Component wear

Analytical Technique	Source
• Si	Contamination
• B	Contamination
• Na	Contamination
• V	Contamination
• K	Contamination
• Viscosity	• Oil degradation, fuel dilution, and soot and other blowby
• Blotter spot test	• Soot, dispersancy, water and/or glycol
• Hot plate crackle test	Water
• pH alkalinity depletion	Strong acid, oil degradation, stoichiometry

If abnormal concentrations are detected, additional analytical confirmatory tests are included:

- Pentane and benzene insolubles by centrifugation
- Water by centrifuge
- Glycol by field test kit (ASTM D 2982-73)
- Fuel dilution by GC or flash point
- Neutralization number

However, these confirmatory tests are not recommended unless drain-on-condition policy is adopted. If so, other tests may also have to be considered, such as microfiltration for particle size distribution and infrared (for oxidation and possibly nitration). Because of the limited specificity of any individual test, accurate diagnostic recommendations may require a series of tests. For example, viscosity is an important lubricant property (in fact, the single most important property); however, deviations from the viscosity norm can be due to a multitude of reasons:

- Lubricant order requiring grade change
- Fuel dilution due to leakage or combustion stoichiometry
- Shearing of polymer thickener or high molecular weight dispersants

- Oil oxidation due to wear stress or blowby effects
- High soot levels due to high blowby or poor stoichiometry
- Emulsion formation due to glycol or water contamination
- Etc.

Diagnosis, prognosis, and maintenance recommendations require specific identification and quantitation of the cause or causes of the abnormal viscosity, hence the extensive listing of confirmatory tests. However, for the most part, the primary tests will tend to identify abnormal wear, contamination or stoichiometry attributed to irregular engine operation or impending engine component failure.

Table 13 is an abbreviated scheme for relating engine condition to abnormal analytical data. The potential engine-related problems corresponding to the analytically measured properties and the causes of abnormal analytical data are outlined in this table.

TABLE 13. SCHEME FOR RELATING ENGINE CONDITION TO ABNORMAL ANALYTICAL DATA

Analytical Property	Indication of Abnormal Condition	Potential Engine Related Problem
Metal		
Iron (Fe)	Iron metal component wear	Check gears, cylinder liners, crankshaft, pumps, supercharger, etc.
Lead (Pb) Copper (Cu) Silver (Ag) Tin (Sn)	Bearing insert wear*	Check inserts and bushings
Chromium (Cr) Aluminum (Al)	Piston liner/ring wear	Impending failure or high wear due to dirt ingestion; blowby increase due to wear
Silicon (Si) Aluminum (Al)	Dirt or dust	Air cleaner not properly operating, air intake leak
Boron (B) Sodium (Na) Chromium (Cr)	Coolant	Check for coolant leak
Crackle Test	High water	Check for low sump temperature Check for coolant leak Is glycol present? (boron and sodium test under metals)
Viscosity		
High	Oil degradation Soot	High cylinder temperature operation Poor stoichiometry
Low	Fuel dilution, use of lubricant of lower viscosity for cold weather operation	Check for injector leaks Check for fuel line leaks Confirm lubrication order
Spot Test	High soot Dispersancy decreased due to water	High blowby Poor fuel-air stoichiometry (rich) Supercharger improper operation Injectors leaking, etc. Coolant leak or low sump temperature operation
pH	Strong acids and alkaline depletion	High-temperature operation, high blowby, or high-sulfur fuel with low-temperature oil operation, oil degradation

* Tin (Sn) may be only flashing and not major metallurgical component

SECTION IV
PROGRAM COSTS

General

This section of the report examines the cost factors involved in the implementation of an Air Force diesel engine oil analysis program. The discussion is based on the use of the physico-chemical tests recommended in Section III, i.e., spectrometric analysis, viscosity, crackle test, pH determination, and blotter spot test. The subsequent discussion assumes that any diesel engine OAP would be integrated within the current Air Force aeronautical OAP and that, ultimately, all Air Force OAP laboratories (presently 104 in number) would acquire a diesel engine oil analysis capability.

Laboratory Equipment Costs

Table 14 lists the proposed laboratory equipment and related costs of procurement. Recommended items include the Nametre viscometer, a standard laboratory hot plate (crackle test), and an industrial grade pH meter with a combination electrode. It is seen that the Nametre instrument comprises by far the major portion of equipment cost. While capillary tube viscometers could be employed at an equipment cost of about one-fourth that of the Nametre unit, it is believed that reduced labor costs for operation of the latter instrument easily outweigh the price advantage for other techniques.

Using the estimated item lives, Table 14 shows an annual equipment cost of $514 per laboratory. The initial cost to equip all of the present 104 laboratories would be $435,760.

Sample Analysis Costs

Analysis costs were computed on a per sample basis. To explore the effect of alternate approaches, three different program plans were considered, described as follows:

TABLE 14. EQUIPMENT COSTS PER LABORATORY

Item	Initial Cost	Yearly Cost*
Nametre viscometer	$3,795	$379.50
Hot plate	45	4.50
pH meter	300	30.00
pH electrode	50	100.00
	$4,190	$514.00

* Based on an equipment life of 10 years and an electrode life of 6 months.

TABLE 15. ANALYSIS COSTS PER SAMPLE

Item	Case I	Case II	Case III
Sampling			
Supplies	$0.30	$0.30	$0.30
Labor*	1.13	1.13	1.13
	$1.43	$1.43	$1.43
Analysis			
Labor* (physico-chem tests)	0.75	---	0.75
Consumables (solvents, glassware, spot paper, etc.)	0.15	---	0.15
Spectrometric analysis**	0.88	0.88	0.88
	$1.78	$0.88	$1.78
Fixed Costs			
Program management	0.06	0.06	0.06
Personnel training	0.05	---	0.05
Data system	0.04	0.04	0.04
Lab equipment	0.77	---	4.87
	$0.92	$0.10	$5.02
	$4.13	$2.41	$8.23

* Based on utilization of an E-4 grade enlisted person at a rate of $4.49/hr.

** Includes only labor and consumables costs.

Case I - spectrometric and physico-chemical testing, all end items

Case II - spectrometric testing only, all end items

Case III - spectrometric and physico-chemical testing, selected end items

Cases I and II include all end items (7,682 units) previously listed in Table 2. Case III was calculated for those four equipment categories identified by Figure 4 as having a high potential for rebuild cost avoidance, i.e., loading vehicles, fire trucks, construction vehicles, and facility equipment. The total number of end items in these groups is 1,220.

Table 15 presents the breakdown of per sample analysis costs for the three cases investigated. The sampling cost of \$1.43 applies to each case, as does the spectrometric analysis cost of \$0.88. The latter may be considered artifically low since the figure does not include costs which are currently borne by the aeronautical OAP, such as spectrometer depreciation and maintenance, facility overhead, and personnel training. However, if these costs were apportioned for a diesel engine OAP, there would be a corresponding decrease in the aeronautical OAP analysis cost per sample.

Under fixed costs, values for program management and the data system are those presently assigned for the aeronautical OAP, while the personnel training cost, applicable to the physico-chemical test procedures, is estimated. The per sample equipment cost (\$514 times 104 labs divided by the number of samples per year) is significantly higher for Case III than Case I because the former plan would involve far fewer samples annually. As a consequence, the total analysis cost per sample for Case III is almost twice that for Case I, with the Case II cost (spectrometric determination only) being the lowest.

Estimated Cost Benefits

The economics and possible cost benefits for each of the three program cases are shown in Table 16. Line (a) lists the total number of end items involved, while line (b) is an estimate of the number (75%) of operable end items at any given time. Line (c) lists the total number of lubricant samples to be ana-

TABLE 16. DIESEL ENGINE OAP ECONOMICS

		Case I	Case II	Case III
a.	Total end items	7,682	7,682	1,220
b.	Est of items in use (75% of a)	5,762	5,762	915
c.	Total samples per year (12 x b)	69,144	69,144	10,980
d.	Analysis cost per sample (Table 15)	\$4.13	\$2.41	\$8.23
e.	Total cost per year (c x d)	\$285.6K	\$166.6K	\$90.4K
f.	Annual rebuild cost (Table 2)	\$505.95K	\$505.95K	\$296.25K
g.	Possible rebuild savings (60% of f)	\$303.57K	\$303.57K	\$177.75K
h.	Breakeven hit percentage (100 x e ÷ g)	94.1	54.9	50.9

lyzed per year, assuming an average engine sampling interval of 1 month. Line (d) is the per sample analysis cost derived in Table 15. Line (e) is the total annual program cost for each case.

In arriving at a value for possible cost savings [line (g)], it is assumed that an effective diesel engine OAP would result in an engine repair action and obviate the necessity for a major engine rebuild. It is estimated that the cost of repair would be 40 percent of a depot rebuild cost. Thus, for Cases I and II, line (g) is 60 percent of the total annual rebuild cost for all end items (Table 2), while for Case III possible savings are 60 percent of rebuild costs for the four selected equipment categories.

Line (h) represents the breakeven hit percentage, or OAP prediction effectiveness, for which the annual dollar savings would equal the total annual program cost. For Case I, this breakeven point (94.1 percent) is relatively high. Even with a 100-percent hit effectiveness, the Case I example would yield a savings of only $18K per year.

The breakeven hit percentage of 54.9 for Case II indicates a significantly greater potential for a savings realization. In this instance, a maximum (100-percent effectiveness) annual savings of $137K is potentially achievable. An alternate economic criterion is the savings/cost ratio, which for Case II is a maximum of 1.82 [the ratio of line (g) to line (e)].

The analysis of Table 16 shows that Case III offers the greatest opportunity for a cost-effective diesel engine OAP. While the maximum annual savings of $87.4K for Case III is less than that for Case II, the former case gives a maximum savings/cost ratio of 1.97. Thus, for every program dollar invested, a maximum return of $1.97 is attainable.

The above discussion presents maximum values for potential savings in terms of a 100-percent hit effectiveness. It is, of course, recognized that a 100-percent hit capability is unrealistic; however, there is no technical basis for assigning a more realistic hit percentage. It is reasonable to assume that the Case III effectiveness using spectrometric and physico-chemical analyses would be greater than that for Case II employing only spectromic analysis. It is also believed reasonable to predict that the Case III effectiveness would easily exceed the 50.9 percent breakeven point.

In an effort to project Air Force benefits from a diesel engine OAP, data from a summary* of the Army oil analysis program (AOAP) for fiscal year 1978 were examined relative to the economic statistics previously cited. Direct comparisons, however, were difficult. The AOAP summary separately listed the numbers of aeronautical and nonaeronautical equipment samples analyzed and estimated savings, but did not (and probably could not) distinguish between the two equipment types with respect to program costs. In an attempt to obtain an approximation of the savings/cost ratio for the AOAP ground equipment effort, total program cost ($2,120,995) was divided by total samples (428,215) to yield an average per sample analysis cost of $4.95. This figure multiplied by the number of nonaeronautical samples (143,484) processed gives an approximate ground equipment program cost of $710,246. Relative to the estimated cost avoidance of $1,936,500 for nonaeronautical engines and transmissions, a savings/cost ratio of 2.73 is obtained.

This figure is not significantly at variance with the maximum ratio of 1.97 previously noted for Case III. (The AOAP hit percentage for ground equipment in FY78 was 98 percent, but maintenance feedback confirmation was submitted for only 35 percent of the total number of laboratory recommendations for equipment inspection.) Any variance might easily be due to differences in the types of equipment being considered. The nonaeronautical AOAP cost avoidance for FY78 was almost exclusively associated with high-output, high-dollar value engines and transmissions for tracked combat vehicles--items of equipment not present in the Air Force inventory.

While a maximum savings/cost ratio of 1.97 for the Case III program is not an impressive return on the invested dollar, there are additional factors which could increase the ratio. For example, certain items within the Case III equipment categories with a high population and low rebuild cost could be eliminated. Additionally, there are apparently numerous items of civil engineer equipment which could not be identified in the classification of Section

* "Army Oil Analysis Program Cost and Operations Summary," US Army DARCOM Materiel Readiness Support Activity, 22 Dec 78.

II. Equipment of this type, as shown in Figure 4, is highly amenable to a cost-effective OAP. Finally, in any assessment of a military OAP, it should be recognized that there are intangible benefits to be derived, e.g., improved materiel readiness, increased equipment utilization, and reduced spares inventory.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of this study, the following conclusions were drawn:

- Through a compilation of Air Force records on diesel engine equipment, an analysis of rebuild costs and rebuild rates identified four equipment classes with a significant potential for oil analysis--loading vehicles, fire trucks, construction vehicles, and facility equipment. A composite record of Civil Engineer equipment at the various bases was not available, and such equipment could not be included in this investigation.

- An overall evaluation of the value of oil analysis for nonaeronautical equipment, in general, did not permit a well-founded conclusion in this regard. Differences of opinion within each group were expressed by responding lubricant suppliers and engine manufacturers. Definitive studies or rigorous correlations were not offered by those favoring the implementation of oil analysis programs. Nevertheless, in view of the extensive investment in personnel and money made by both the commercial and military (AOAP) sectors, it may be inferred that a large segment of those organizations concerned with diesel engine maintenance and utilization is convinced of the effectiveness of oil analysis.

- A survey of recommended current practices and techniques for oil analysis was conducted with emphasis on applicability, cost, and performance simplicity. It was concluded that the following determinations represent the optimized set of test procedures for engine condition surveillance:

  (1) Spectrometric analysis
  (2) Viscosity by vibrating sphere
  (3) Crackle test
  (4) pH measurement
  (5) Blotter spot test

- An economic analysis of diesel engine OAP costs indicated no justification for inclusion of all available equipment in a program utilizing all recommended test procedures. A maximum savings/cost ratio of 1.82 was estimated for a program applied to all equipment items employing only spectrometric analysis. The most economically beneficial program of those examined would be that limited to the equipment categories listed above, employing both spectrometric and physico-chemical analyses. This approach yields an estimated savings/cost ratio (maximum) of 1.97.

While the investment return for the latter program is only marginally attractive, additional selectivity could be applied to the equipment included in the program to improve cost avoidance. Intangible benefits will also be realized from an effective diesel engine OAP. Nevertheless, it is not recommended that a diesel engine oil analysis program be fully implemented at this time. It is not felt that the initial cost ($435,760) required to equip all existing OAP laboratories can be justified on the basis of present knowledge.

It is recommended that a pilot program be instituted for a limited number of laboratories to investigate more practicably the benefits of the effort. Such a pilot program would also provide a foundation for development of personnel skills, refinement of analytical procedures, and the evaluation of unique analytical techniques which have not been fully documented for use. In the latter area, it is envisioned that some evaluation of the various conductivity instruments and field test kits is warranted.

With respect to selection of those OAP laboratories to be included in a pilot program, locations which have a high population of the four equipment categories previously identified is desired. For this purpose, it is recommended that the five ALC laboratories (Oklahoma City, Ogden, San Antonio, Sacramento, and Warner Robins) are likely candidates. The three laboratories (Dover, McChord, and McGuire AFB) within the continental United States serving the Military Airlift Command are also proposed candidates. The initial cost of laboratory instrumentation to equip these eight OAP labs would amount to an expenditure of approximately $33,520.

APPENDIX

ASSESSMENT OF THE STATE-OF-THE-ART IN USED OIL ANALYSIS THROUGH A REVIEW OF THE LITERATURE

In the process of recommending analytical techniques and sampling procedures as a part of the deliberation of the feasibility of including diesel engine-powered ground equipment in the U.S. Air Force Oil Analysis Program (OAP), a current background of knowledge of the state-of-the-art in used oil analysis was required. This Appendix attempts to provide an assessment of the state-of-the-art in used oil analysis with emphasis on diesel internal combustion engines (ICE) through a review of the literature. Bibliographic references are included within this text as often as possible so as to provide an annotated review.

During December 1978, a literature search was performed using the following search bases:

- o NTIS: Retrospective to 1964, prepared by the National Technical Information Service of the U.S. Department of Commerce.
- o Chemical Abstracts Condensats: Condens/CASIA, 1970-1971, 1972-1976, 1977 to present, prepared by Chemical Abstracts Service.
- o SAE Abstracts: Abstracts prepared by Society of Automotive Engineers.

For the NTIS search, the program scans all abstracts in the file for the given keywords or key letter sequences:

Set 8	Set 19	Set 23
Analy	Used Oil	Method
Prognos	Used Oils	Technique
Diagnos	Lubrica	
Monitor	Oil	
Exam		
Evaluat		
Test		

Since 1964, there are 712 citations which show at least one member from each of the above sets. That is, each of those 712 abstracts contains one member of set 8, one member of set 19, and one member of set 23. Of the 712 abstracts, 585 date from 1970 forward, and these are the ones which were reviewed.

Chem Abstracts was searched in the same manner as the NTIS with one exception. The three sets used in the NTIS search were used in the Chem Abstracts search and one other set was added; that set contained the word "diesel". This search gave a total of 30 citations since 1972.

The SAE Abstracts data base was scanned in the same manner as with NTIS and Chem Abstracts but using only set 8 and set 19. This search gave 603 abstracts since 1965. These abstracts (and pertinent papers or reports) were reviewed, and selected references were included in the preparation of the following annotated review which has been divided into three sections. An alphabetized bibliography is provided after the last section.

I. MILITARY VIEWPOINT

From a military viewpoint, a recent report prepared by the Comptroller General of the United States provided a review of the activity in spectrometric oil analysis (SOA) and identified areas of potential improvement in the utilization of military SOA (1)*. Inferrred savings were identified for ground equipment based on examples of private industrial cost-effective programs. Particular emphasis was placed on cost savings potential permitted through the factual and scientific help which SOA could provide in extending individual oil change intervals. Extending these oil change intervals would save oil, maintenance manpower, and equipment downtime, while still protecting the equipment from excessive wear and failure. A major Department of Defense (DoD) "drain on condition" thrust area identified by a DoD project manager (for Mobile Electric Power) is the more than 26,000 generators in the then current DoD inventory (2) which have 100-hour oil change intervals. These generators

* Numbers underlined in parentheses refer to references at end of each section.

potentially be changed at 300 hours (or every 6 months), resulting in a very significant cost savings.

The joint "Industry-Military Spectrometric Oil Analysis Symposium" was held July 18-20, 1967 in San Antonio, Texas. This Symposium summarized much of the background in the use of spectrometric oil analysis programs (SOAP), which predominantly addressed wearmetals. The Symposium discussed the relation of SOAP to aircraft engines and industrial (stationary and vehicular) engines. This Symposium lent support to the formation and acceptance of a tri-service agreement between the Army, Navy, and Air Force to ensure systematic planning, developing, and managing of a coordinated SOAP program within the DoD.

An Army fleet test was initiated in September 1967 (under contract DAAD05-67-C-0361) at Southwest Research Institute, and oil samples were submitted for detailed analysis in support of providing input to an evaluation of SOAP as applied to Army tactical vehicles (3).

The DoD Equipment Oil Analysis Program was established by DoD directive under the management of the Navy in May 1969. This DoD directive was replaced with a "Joint Agreement for the Interservice Equipment Oil Analysis Program" dated 2 October 1972, and it continues to be the basis of an on-going program known as the "Joint Oil Analysis Program (JOAP)," directed by the OAP managers for each of the services, Army, Navy, and Air Force.

The Army Oil Analysis Program cost and operations summary (4) provided for FY78 showed 428,215 oil samples (aero and nonaero) analyzed at nine laboratories for a cost avoidance to cost of program ratio of 20 to 1. The highest number of nonaeronautical samples (47,019) were analyzed at Ft. Hood, Texas, where, coincidently, a high population of active diesel engines is located.

While the Army program appears to be successfully cost effective, it is actually in a growth pattern in that not all engine oil samples are analyzed other than for metals. The physical property testing has been expanded in support of "on condition" oil change recommendations, the cost effectiveness of which has yet to be proven. (See Section III of this report for a more thorough discussion of the laboratory test practices at AOAP laboratories).

A number of technical bulletins have been published which describes the Army Oil Analysis Program (5,6).

A bibliographic listing of articles and reports addressing oil analysis, cross indexed by subject and author, has recently been compiled by the Military Joint Oil Analysis Program (7). Unfortunately, while topics are keyed to the 1,001 references in this compilation, no abstracts are provided.

References

1. Comptroller General of the United States, "Single Manager Needed to Obtain Cost and Fuel Savings in Spectrometric Oil Analysis Program," Report to the Congress, LCD-75-431, 31 August 1975.

   This report indicates that, historically, the railroad industry originated SOA in the 1940's. The Navy began using SOA for military aircraft in 1955, and the Army and Air Force SOA programs began in 1961 and 1964, respectively. This report identifies the potential savings from using oil analysis for nonaircraft equipment by reducing maintenance costs and extending oil change intervals. Some convincing cost-effective SOA approaches by private industry are exemplified for:

   - A large construction contractor,
   - A leading producer of heavy construction equipment through increased oil change interval time,
   - A railroad's locomotives,
   - A municipality's fleet of 205 vehicles, and
   - A commmercial trucking fleet of 185 trucks.

2. Gurshi, C.R., et al., "Extended Oil Change and Oil-Filter-Change Intervals for DoD 5-200 Kilowatt DED Generator Sets," MERADCOM Report Number 2234, March 1978.

3. Stavinoha, L.L., and Quillian, R.D., Jr., "Spectrometric Metals Analysis of Oil-Army General Purpose Vehicles," Final Report AFLRL No. 5, AD 685886, October 1968, Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314.

4. No Author, "Army Oil Analysis Program Cost and Operations Summary," U.S. Army DARCOM, Materiel Readiness Support Activity," Lexington, Kentucky, 22 December 1978.

5. No Author, "Nonaeronautical Equipment Army Oil Analysis Program (AOAP)," Department of the Army Technical Bulletin, TB 43-0210, Headquarters, Department of the Army, Washington, D.C., 22 July 1978.

Includes sections on:

- General purpose, scope, definitions, etc.,
- Responsibilities,
- Initial entry into AOAP,
- Sampling requirements, techniques, intervals (25 operating hours or every 30 days, in most cases),
- Feedback data (in the form of recommendations),
- Laboratory locations (nine),
- Limitation of analysis, and
- Specific appendices for applying AOAP to (1) AVDS 1790 diesel engine series, (2) 6V53, 6V53T, and 8V71T engine series, (3) diesel electric locomotives, (4) watercraft, and (5) material handling and construction equipment.

6. No Author, "AOAP Army Oil Analysis Program Users Guide Nonaeronautical Equipment," Technical Bulletin TB 43-0211, Department of the Army, Washington, D.C., 30 January 1978.

Provides pictorial approach to accomplishing sampling, documentation, shipment of sample to laboratory, and follow-up instructions. For policies, objectives, and responsibilities, see AR 750-22.

7. No Author, "Joint Oil Analysis Program Bibliography," Final Report JOAP-TSC TR-78-001, Technical Support Center, Joint Oil Analysis Program, Naval Air Station, Pensacola, Florida 32508, July 1978.

In addition to "Work Unit Summaries" and a bibliographic index, the bibliography contains 1,001 references. The references include the title of each entry, which has been placed in alphabetical order according to author's last name. Topics keyed to the references include:

- Elements (24 individual elements listed)
- Additives
- Additives - Analysis
- Analysis - Colorimetric, Metals
- Analysis - Fluids (General)
- Analysis - Metallic, Chemical - instrumental and unclassified
- Analysis - Neutron Activation
- Analysis - Radioactive
- Analysis - Trace Metals (General)
- Analysis - Wearmetal (General)
- Assessment, Fluid
- Condition, Fluid
- Corrosion
- Debris, Wear

- Diagnosis, Machine
- Ferrography
- Filters, Filtering
- Fluids (Hydraulic), Fluid Systems, and Contamination
- Greases, Solid Lubes, Boundary Lubes
- Life - Engine, Machine, Bearing, Gear
- Lubrication and Lubricants
- Luminescence, Chemical
- Maintenance
- Monitoring, Engine Health
- Performance, Fluids
- Prognosis, Machine
- Reclamation, Fluid
- Specifications
- Spectrometry, Atomic Absorption
- Spectrometry, Atomic Emission
- Spectrometry, Atomic Fluorescence
- Spectrometry, Electron/Resonance
- Spectrometry, Fluorescence and X-Ray
- Spectrometry, Infrared
- Testing and/or Evaluation, Machine
- Wear, Wear Studies, Tribology

II. OIL ANALYSIS IN GENERAL

A set of references (8-53) was reviewed, summarized, and categorized as reflecting oil analysis in general. While much of this topic is covered primarily by selected papers published by the Society of Automotive Engineers, other sources are included.

Oil analysis programs involve communication between the laboratory (where analyses are performed and data are archived), the user (who withdrew the oil sample and sent it, along with pertinent engine information to the laboratory), the repair facility (which confirms or denies the existence of a distressed component), and management (who must decide on the cost effectiveness and criticality of the used oil analysis program). The following list of terms (or words in some cases) forms a basis of OAP communication and has been elaborated on in references 41 and 64.

- Removal - Taking a component to repair shops for any reason.
- Hit - A removal for which OAP prediction was found to be justified.
- Miss - An OAP-based removal not found to be justified.

- Success - The percentage of OAP-based removals which are hits.
- Fail - A removal caused by field evidence (noise, vibration, smoke, etc.) which should have been predicted by OAP, but was not.
- Diagnosis - The act of recognizing or determining what component/components are abnormal and their mode/modes of abnormality. Detection of the problem.
- Prognosis - Definition of the course of the component or machine abnormality to include time to failure and abnormality mode progression.
- Recommendation - Defined course of corre tive action.
- Detection - Determining that elements of oil analysis (analytical data) are normal or abnormal.
- OAP Prediction - Recognition or suggestion of an impending failure of an engine component due to abnormal element detection.
- Impending Failure - Total or complete failure not yet having occurred but diagnosed as pending.

The condition of internal combustion engine (ICE) oils is approached somewhat differently than is the condition of turbine engine oils. Metals generally found in used ICE lubricating oils are from three sources--wear, contamination, and additives. Table A.1 lists the more common metals and shows which metals can be from one or more of the wear, contamination, or additive sources. Table A.2 lists those metals related to dirt, coolant, and fuel contamination of oil.

Since the ICE oil must lubricate, as well as cool and keep the engine clean, the ICE oil condition becomes important. Three basic factors in diesel engine lubrication have been identified as soot, sulfur, and severe temperature by K.L. Kreuz in a discussion of diesel engine chemistry as applied to lubricant problems (8). ICE oil must contend with piston blowby of combustion products, including carbon, nitrates, oxygenates, etc., as well as raw fuel. Each of these can reduce the lubricating ability of an oil premature to a normal or extended oil drain interval. Each engine has an additional "oil con-

TABLE A.1. METALS IN DIESEL ENGINE OILS

Wear	Contaminant	Additives
Fe	Si	P
Pb	Pb*	Zn
Cu	B	B**
Cr	Ca	Ca
Al	Al	Ba
Ni	Na	Na**
Ag	V	Mg
Sn	Cr	
Mo	K	
Mn		

* Seldom unless leaded gasoline present in fuel.
** Minimized by oil specification

TABLE A.2. METALS FOUND IN CONTAMINANTS

Contaminants	Metal
Dirt	Al, Si, Ca
Coolant	B, Cr, K, Na
Gasoline	Pb
Diesel	V

sumption factor" (whether the oil is burned or simply leaked by seals) which can significantly influence laboratory data results with respect to their diagnostic interpretation.

Dispersancy can be a key to oil condition and may be best measured by pore-sized filters rather than simple "pentane-insolubles" and is the subject of ongoing research at laboratories such as Shell Research Laboratories and cooperative testing within the Technical Division D-2 of the American Society for Testing and Materials. Independent of ICE oil insolubles (measured by any method) or dispersancy (measured by such tests as the "spot test,") carbon from diesel engines may affect other additives such as some extreme pressure additives (potentially) by adsorption. Thus, the additive is rendered ineffective, resulting in excessively high wear rates of certain high load areas of IC engines (35). Assuming wearmetal concentrations will detect this default, oil additive compounds would be changed or oil change intervals shortened since no simple laboratory test has been defined to relate to the friction increase due to this kind of chemical adsorption process.

While probably not totally exhaustive, used oil properties have been identified in Table A.3 under contamination, metals, and oil degradation for which the type of analytical methods and significance have been indentified.

Used oil analytical data are related to engine condition and/or operation in Table A.3 which also identifies the probable cause of abnormal test data results. Table A.4 is a broadly generalized cause-and-effect relationship for diesel engine condition and/or operation.

Normal wearmetal production (assuming normal drain intervals) can be described pictorially as below.

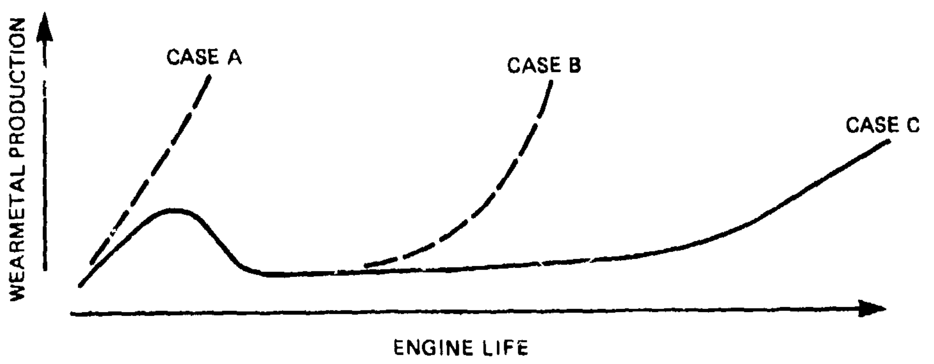

TABLE A.3. USED OIL PROPERTIES, ANALYTICAL METHODS, AND SIGNIFICANCE

Category	Analytical Method	Significance
Contamination		
Water and/or ethylene glycol	Various direct water and/or ethylene glycol methods	High-value impairs lubrication, emulsifies oil
Dirt, dust	Spectrographic for silicon	Causes abrasive engine wear, especially if ingested
Fuel	Flash point, viscosity, or direct analysis for fuel	Lowers viscosity of lubricant
Combustion blowby products:		
Soot	Insolubles, blotter soot test, viscosity, infrared optical density	Increases viscosity, can agglomerate and form sludge, plugs oil filter
Oxygenates	Acid no., pH Infrared for carbonyl	Viscosity increase due to polymerization, corrosivity
Reactive hydrocarbons	—	Viscosity increase due to polymerization, corrosivity
Sulfate-containing compounds (e.g., H_2SO_4)	Acid no., pH	Viscosity increase due to polymerization, corrosivity
Nitrogen-containing compounds (e.g., HNO_3)	Acid no., pH	Viscosity increase due to polymerization, corrosivity
Metals	Spectrographic metals	
Aluminum (Al)		Engine wear or dirt contamination
Chromium (Cr)		Engine wear or coolant contamination
Copper (Cu)		Engine wear
Iron (Fe)		Engine wear

TABLE A.3. USED OIL PROPERTIES, ANALYTICAL METHODS, AND SIGNIFICANCE (Cont'd)

Category	Analytical Method	Significance
Metals (cont'd)		
Lead (Pb)		Engine wear or gasoline contamination
Silver (Ag)		Engine wear
Tin (Sn)		Engine wear
Nickel (Ni)		Engine wear
Silicon (Si)		Dirt contamination
Boron (B)		Coolant contamination
Potassium (K)		Coolant contamination
Sodium (Na)		Coolant contamination
Magnesium (Mg)		Lubricant additive package
Barium (Ba)		Lubricant additive package
Calcium (Ca)		Lubricant additive package
Zinc (Zn)		Lubricant additive package
Phosphorus (P)		Lubricant additive package
Oil Degradation		
Oxidation	Acid number Carbonyl by infrared	Causes increased viscosity, engine varnish, sludge, and promotes metal corrosion
Shearing of oil and viscosity index improvers	Viscosity	Lowered viscosity

TABLE A.4. CAUSE OF OIL ANALYSIS TEST RESULTS RELATED TO DIESEL ENGINE CONDITION AND/OR OPERATION

Cause of Oil Condition	Relation to Engine Condition and Operation
Water condensation	Low cooling jacket temperature Inadequate crankcase ventilation Excessive engine idling at cool temperatures Short, intermittent service
Water and ethylene glycol coolant leakage	Improperly torqued cylinder head Defective or blown gasket Defective seal Improper installation of seals Cracked block or cylinder head
Diesel fuel dilution	Overfueling due to restricted fuel return line or oversize injectors Poor injector spray pattern Dribbling from burnt or defective injector tips Restricted air supply or exhaust system Worn rings and liners Ring sticking or breakage
Oil degradation	High temperature operation due to peak power output, inadequate cooling, or lean operation Engine wear excessive Over-extended oil drains or poor oil specification
High blowby fuel soot	Rich operation due to overfueling, restricted air intake or exhaust system Defective injectors causing poor spray pattern or dribbling nozzles Worn rings or liners, stuck or broken rings
Ingested dirt	Inadequate air filter maintenance Air leaks in intake system
Wearmetal	Piston, piston liner/ring metals generally related to quantity of ingested dirt Inadequate oil filter maintenance Poor lubrication or worn out parts Normal wear
Increase in total acid no.	
Slow or moderate	Normal blowby production
Rapid	High blowby or oil degradation (see above)

TABLE A.4. CAUSE OF OIL ANALYSIS TEST RESULTS RELATED TO DIESEL ENGINE CONDITION AND/OR OPERATION (Cont'd)

Cause of Oil Condition	Relation to Engine Condition and Operation
Increase in strong acids	Poor combustion, high blowby sulfuric acid condensation due to low cylinder wall temperatures High-sulfur fuel when oil drain extended, depleting of oil over-basing
Decrease in total base no.	
Slow	Normal operation, normal fuel sulfur level
Rapid	High blowby and oil oxidation

The dotted line failure cases A and B represent infant engine mortality and premature engine failure, respectively. Case C is the normal breakin, followed by normal wearmetal production observed when the engine life is maximized. Successful SOA requires detection of wearmetals production from an impending failure rather than a catastrophic failure, resulting in a repairable rather than a rebuildable engine situation, respectively. Normal wearmetal production as measured by SOA depends on engine type and service, lubrication change interval, and oil-consumption rate. Trend analysis for a group of similarly operated engines seems to be most successful for detecting impending failures of oil-wetted components. Particular individual and sets of metals must be related to oil-wetted components in order to identify failing components. The most success has been in the piston cylinder/liner/ring, rod and main bearing insert and gear areas of engines. That is, wearmetal production from cam lifter surfaces and valve stem areas for example, is generally not diagnostically significant.

Effective engine condition montoring may also require vibration analysis, boroscopic inspection, chip-detector inspection (micro and macro), oil-filter evaluation, engine-operating condition information including oil consumption, and sophisticated data interpretation and recommendation schemes. Additionally, the lubricating oil placed in a system must respond to tests diagnostically reflecting its condition and the condition of the engine or transmission it is lubricating.

References

8. Kreuz, K.L., "Diesel Engine Chemistry," Lubrication, 56, No. 6, pp 77-88 (1970), Texaco Inc., 135 East 42nd Street, New York, New York 10017.

9. Snook, W.A., "Used Engine Oil Analysis," Lubrication, 54, No. 9, pp 97-116 (1968), Texaco Inc., 135 East 42nd Street, New York, New York 10017.

The relation of used oil crankcase oil analysis to engine condition or operation and oil life was summarized in a discussion of used engine oil analysis. Basic used oil tests included:

- Appearance and odor
- Water
- Viscosity
- Flash point
- Insolubles
- Neutralization or base number
- Ash content
- Trace metals

10. Kochanski, K.B. and Leiby, D.W. (General Electric Co.), "Design Integration--The Key to Effective Engine Condition Monitoring," SAE Paper No. 710447.

The mechanical health of aircraft engines is assessed through such techniques as parameter monitoring, vibration analysis, oil monitoring, boroscopic inspection, and radiography, to provide problemdetection, isolation, and trend monitoring.

11. Butler, J.L., Stewart, J.P., and Teasley, R.E. (Cummins Engine Co.), "Lube Oil Filtration Effect on Diesel Engine Wear," SAE Paper No. 7108-13.

Tests indicated that bypass lube oil filtration combined with good full-flow lube oil filtration result in lowest engine wear rate and lowest total cost for the engine user.

12. Lotan, D. (Socie A.A. Nat'l d'Etudes et de Constructio), "Spectrometric Oil Analysis--Use and Interpretation of Data," SAE Paper No. 720303.

Based on turbojet engine investigations, the mathematical statement of the functioning of an oil system is presented along with the parameters governing the oil system, a chart for interpreting spectrometric oil analysis data is developed, and the mathematical theory is worked out in detail.

13. Stavinoha, L.L. and Wright, B.R., (Southwest Research Institute), "Spectrometric Analysis of Used Oils," SAE Paper No. 690776.

The techniques and diagnostic significance of atomic absorption, atomic emission, and infrared spectrometric analysis of crankcase lubricants are discussed with the use of supplementary data where pertinent. The parameters affecting used oil analytical data are discussed in terms of examples from Army general-purpose vehicle test engines. Wearmetals in used gear oils are also discussed, and examples are given. Analytical methods and their applications are fully described, and the equipment and procedures for infrared spectroscopic and gas chromatographic techniques are outlined.

14. Waddey, W.D. and Pearce, A.F. (Esso Research and Engineering Co.), "Effects of Motor Oil Composition on Engine Wear," SAE Paper No. 690-774.

With an optimum balance of components, multigrade oils can be designated which are as effective in controlling wear as single-grade oils.

15. Ingram, R.B. (Avco Lycoming Div., Avco Corp.) "Time Between Overhaul as Related to Modern Engine Design and Maintenance Techniques," SAE Paper No. 710381.

Time between overhauls can be practicably increased for certain air-cooled aircraft piston engines through the modern use of engine design, materials, and maintenance technology, including the use of spectrographic oil analysis (SOAP).

16. Asseff, P.A. (Lubrizol Corp.), "Engine Performance as Influenced by Lubricant Deterioration," SAE Paper No. 680760.

Viscosity, insolubles buildup, contamination with metals, fuel, water, glycol, and other physical and chemical changes are considered in the evaluation of used lubricating oils. Engine operation and performance are related to the oil condition in varying degrees of relative significance. Engine wear may be associated to pentane insolubles and total acid number.

17. Frassa, K.A. and Sarkis, A.B. (Mobil Oil Corp.), "Diesel Engine Condition Through Oil Analysis," SAE Paper No. 680759.

Infrared analysis, membrane filtration, and atomic absorption spectroscopy results correlated closely with diesel oil and engine condition in automotive and railroad diesel fleet tests. Reliable control of oil-drain intervals and maintenance practices are provided by giving accurate guidelines on oil degradation, oil contamination, engine wear, and engine malfunction. High engine wear severity affects oil degradation and contamination with a resultant effect on recommended oil drain intervals.

18. Wright, R.H. (Penn Central Co.), "Oil Condemning Limits as Established by Used Oil Analysis," SAE Paper No. 680758.

Diesel oil drain interval criteria are discussed for railroad diesel engines. Particular emphasis is placed on blotter spot testing and potential modifications to increase the spot test meaningfulness. Oil condemning limits are presented and reviewed.

19. Frassa, K.A., Siegfriedt, R.K., and Houston, C.A. (Mobil Oil Co.), "Modern Analytical Techniques to Establish Realistic Crankcase Drains," SAE No. 650139 (915D).

Reviews history of used oil analyses in support of evaluating the suitability of an oil for further service and the need for more realistic evaluation test methods. Differential infrared and membrane filtration techniques are discussed and related to predicting engine deposit formation and establishing realistic crankcase drain intervals. The serious shortcomings of then conventional used oil analysis methods are demonstrated.

20. Brown, P.I. (Chevron Research Co.), "Filtration Experience With Highly Dispersant Diesel Engine Oils," SAE Paper No. 670957.

Improved filtering afforded by highly dispersant oils was shown not to affect control of abrasive wear in diesel engine service while filter life was improved.

21. Thomas, G.E. (Southwest Research Institute), Culbert, R.M. (Farr Co.), "Ingested Dust, Filters, and Diesel Engine Wear," SAE Paper No. 680536.

Several basic air cleaners were evaluated using a radioactive tracer technique for their effectiveness in reducing ring wear due to ingested dust.

22. Klug, R.L. (Caterpillar Tractor Co.), and Oelschlaeger, M.F. (Martin Marietta Corp.), "A User's Experience With Oil Analysis," SAE Paper No. 720372.

Oil analysis as a maintenance tool in the construction and aggregate industries done on a continuing basis and properly administered can be cost effective through reduced maintenance costs and improved machine availability. Products of wear can indicate the mechanical condition (of engines, final drives, transmissions, and hydraulic systems), using laboratory equipment and techniques which allow analysis in the field.

23. Bendiksen, O.O. (Pacific Airmotive Corp.), "Improved Failure Detection Techniques Based on Spectrometric Oil Analysis Data," SAE Paper No. 730344.

Calculation of wearmetal liberation rates, correction for oil-consumption effects, and quantitative correlation analysis for diagnostic purposes have been developed to improve the capability of spectrometric oil analysis to detect failures of oil-wetted components in <u>turbojet</u> engines.

24. Otto, O.M. (Gulf Research and Development Co.), "A Practical Application of Engine Observations and Used Gas Engine Oil Analysis," SAE Paper No. 730744.

A used natural gas engine crankcase oil analysis procedure has been assembled to provide practical engine control data which permits the operator to prepare historical engine charts suggesting or predicting needed engine maintenance.

25. Forsman, C.R. (Mobil Research and Development Co.), and Schewindeman, W.R. (International Div., Mobil Oil Corp.), "Benefits of Modern Diesel Engine Diagnostic Tools in Fleet Maintenance and Engine Testing of Fuels and Lubricants," SAE Paper No. 730678.

Electronic diagnostic equipment (for injection pressure curves, combustion pressure patterns, and compression quality) used in fleet maintenance has provided significant savings by detecting incipient breakdowns in time to make repairs and avoid engine replacement and on-the-road failures.

26. Nostrand, W.G. (Nelson Industries, Inc.), "Engine Lubricating Oil Filtration: A Paradox of Variable Constants," SAE Paper No. 740518.

The roles of filtration and filter requirements are discussed, and the four basic filtration systems for engine lubricating oils are described.

27. O'Hara, J.P., Sarkis, A.B., Kennedy, W.A. (Mobil Oil Corp.), "Equipment Condition Through Customized Oil Analyis," SAE Paper No. 730745.

An automated and computerized used oil analysis system provides early warning of potential problems and imminent equipment damage, monitors wear and dirt levels, pinpoints engine conditions causing oil degradation, and recommends corrective action. Laboratory techniques include differential infrared analysis, membrane filtration, viscosity, and wear-metal analysis. The system reduces both analysis and reporting time and has proved to be a valuable predictive maintenance tool.

28. Poley, J. (Analysts, Inc.), "The Practical Application of Lubricant Testing to Equipment Maintenance," SAE Paper No. 740535.

Oil sample collection and data retrieval, spectrometric metallic oil constituents, selected physical tests, and interaction between laboratory and end-item user are important aspects discussed regarding an oil-analysis program. The technique and rationale of data analysis and the conditional statement of equipment and lubricant condition are discussed, based on oil analysis data.

29. Poley, J. (Analysts, Inc.), "Oil Analysis Applications to Off-Highway Equipment," SAE Paper No. 740658.

Off-highway and similar equipment benefit in improved reliability, reduced downtime, and identification of needed repairs through the use of a comprehensive oil analysis program are discussed. The significance and interpretation of test results and practical maintenance recommendations are discussed, and examples of case histories are provided.

30. Westcott, V.C. (Trans-Sonics, Inc.), "Ferrographic Oil and Grease Analysis as Applied to Earthmoving Machinery," SAE Paper No. 750555.

Reviews approach, history, success, etc. of spectrometric metals analysis as a maintenance aid. Ferrographic oil analysis provides wear-particle size distribution and direct-type analysis, thus allowing determination of the nature of a mechanical failure. Wear particles belong to unique classes, and certain types are associated with specific modes of wear, permitting the prediction and nature of an impending machine failure.

31. Boone, E.F. and Didot, F.E. (Suntech, Inc.), "Field Experience of Extended Drain Interval in Diesel Lubricant Performance," SAE Paper No. 760719.

Periodic oil samples of four oil formulations field tested in three types of truck diesel engines were analyzed in a 100,000-mile drain interval test. Engine inspections at 100,000 miles indicated much longer oil drain and filter change intervals are possible with current engine and oil technology.

32. Land, M.L. (STP Corp.), Winer, W.O. (Engineering Consultant), Schwartz, C.F. (Automotive Consultant), "A New Look at Wearmetal Analysis," SAE Paper No. 770085.

Wearmetal generation influenced by contaminants and wearmetal levels in general have been useful in avoiding expensive maintenance or in spotting unusual engine conditions. Industry-developed guidelines indicative of dangerous metal concentration levels have, in general, neglected oil consumption and addition (oil makeup) effects on metal concentrations which, when properly related, can establish wear rates.

33. Asseff, P.A. (The Lubrizol Corporation), "Used Engine Oil Analysis--Review," SAE Paper No. 770642.

Used engine oil analytical tests and their potential significance in evaluating used lubricants are reviewed. A method for more complete pentane and benzene insolubles recovery is described.

34. French, C.E., and Wulfhorst, D.E. (Cummins Engine Co., Inc.), "Field Evaluation of Oil Analysis as a Maintenance Tool," SAE Paper No. 770-644.

Oil analysis failed to show a significant maintenance reduction cost for a sample and control groups in a line-haul, inter-city, and two mining fleets. While oil analysis was found most effective in detecting air intake leaks and contamination by coolant and fuel, the oil analysis effectivess was hindered by irregular sampling, sample contamination, and lack of follow-up.

35. Rounds, F.G. (GM Research Laboratories), "Carbon: Cause of Diesel Engine Wear," SAE Paper No. 770829.

36. Hofman, M.V., and Johnson, J.H. (Michigan Technological Univ.), "The Development and Application of Ferrography to the Study of Diesel Engine Wear," SAE Paper No. 780181.

An in-depth description and applications of ferrographic oil analysis techniques are presented. Ferrography, spectroscopy, and radioactive tracer methods and their abilities to measure wear are discussed. Engine oil operating time, oil and coolant temperature, and filtration effects are demonstrated. Wear rates are shown for a direct injection, four-cycle, turbocharged diesel engine.

37. Strigner, P.L. and Kallio, N.N. (National Research Council of Canada), "A Study of Oil and Filter Change Periods and Engine Oil Monitoring for GM 6V-71 Diesel Bus Engines," SAE Paper No. 780184.

After operation of 13 buses for 7 years having various oil/filter periods of 6,000/6,000 to 25,000/25,000 miles, the optimum oil/filter change interval was judged to be 25,000/12,000 miles. Correlations and oil test data are given.

38. Alexander, W.R., Murphy, L.T., and Silver, R.D. (Mack Trucks, Inc.), "Developing an Engineered Systematized Maintenance Program for Heavy-Duty Trucks," SAE Paper No. 780430.

Extended maintenance intervals are developed for engine oil, gear oil, chassis grease, and the various filters required.

39. Scheller, K. and Eisentraut, K., "Statistical Analysis of Wearmetal Concentration Measurements in Oil: Calculation of Significant Wearmetal Production Rates," Proceedings of the 20th Meeting of the Mechanical Failures Prevention Group, May 17-19, 1977, NBS Special Publication 494.

Regression analysis and compensation for oil consumption greatly improves wearmetal concentration in evaluating engine service life.

40. Tessmann, R.K. and Maroney, G.E., "Effective Fluid Analysis of Oil-Wetted Systems Through Proper Planning and Interpretation," ibid.

Five fluid analysis techniques in widespread use are particle counting, gravimetric analysis, pad comparison, ferrography, and spectrographic analysis requiring proper planning and interpretation to determine corrective actions and cause of failures to provide longer life of oil-wetted components.

41. Senholzi, P.B., "Oil Analysis/Wear Particle Analysis," ibid.

Extensive presentation of the Naval Air Engineering Center's "Oil Analysis Decision Process," designed to replace trial-and-error approaches with the goal of placing oil analysis on a firm technical basis.

42. Rester, G.F., "Application of Ferrographic Lube Oil Analysis to U.S.N. Ship Systems," ibid.

NAVSEC considers ferrographic oil analysis a modern tool of maintenance engineering particularly useful at the maintenance activity level by technicians familiar with the mechanical equipment and trained in ferrography. Advantages and disadvantages of location of equipment are compared.

43. Valori, R., "Effectivness of the Real Time Ferrograph and Other Oil Monitors as Related to Oil Filtration," ibid.

A developmental real time ferrograph was evaluated and found to be effective in detecting scoring and contact fatigue-type failures of bearings and discs if filtration levels exceed 40-micrometers.

44. Bowen, E.R. and Westcott, V.C., "Ferrographic Separation of Organic Compounds," ibid.

Ferrographic separation of organic compounds is potentially a method of assessing wear of seals and gaskets in hyraulic fluid systems.

45. Snowden, J.E., Conway, J., Sr., Westerheid, J.P., "Oil Analysis as a Significant Factor in Oil and Equipment Maintenance," ASLE, 32, 8, pp 425-432 (1976).

Emphasizes the benefits derived by use of modern used oil analysis programs employing emission spectrometry, neutralization number, infrared analysis, and membrane filtration. Basic elements of a good oil analysis program must include:

- establishment of equipment data base
- establishment of deviations from norm due to malfunctions
- metallurgical composition and operating parameter data
- equipment failure causes
- establishment of sampling periodicity
- establishment of meaningful statistical studies of analysis data to provide guidelines for wearmetal and lubricant control limits.

46. Schilling, A. (Chief Engineer, Institut Francais du Petrole), Automobile Engine Lubrication, 1972, Scientific Publications (GB), Ltd. distributed in the USA by Scholium International Inc., Flushing, New York.

    Chapter 10 covers "Lubrication and Maintenance Control," with a section on "Lubrication Control by Examination of Oil During Running." Gives an extensive discussion of rapid elementary analyses with much emphasis on blotter spot tests. Under section on "Through Rapid Analyses," modern techniques including spectrometric metal analyses, differential analyses, and microfiltration are discussed. Under section on "Standard Analyses for New and Used Engine Oils," an extensive listing of principal physical and chemical properties and their significance and interpretation for both new and used oils are given. General condemning limits are given for some lube oil properties including flash point, pentane insolubles, viscosity, and water.

47. Hart, W., Hulme, C.E., and Crumley, R.C., (Whitco Chemical Co.), "Minimizing Fleet Maintenance Costs Through Modern Methods of Crankcase Oil Analysis," National Petroleum Refiners Association, Paper FL-67-61A, Presented at Fuels & Lubricants Meeting, September 13-14, 1967.

    What is the condition and the suitability of a used oil for "continued use" and "are engine malfunctions occurring?"

    Conventional analytical methods:
    - Viscosity
    - Insolubles
    - pH
    - Acid number
    - Base number
    - Water content
    - Fuel dilution
    - Antifreeze content
    - Microscopic examination

    Performance parameters:
    - Degree of oxidation
    - Varnish-forming tendency
    - Contaminant content

- Sludge-forming tendency
- Engine condition

New analytical methods:

- Direct-reading spectrograph for metals
- Infrared spectrometer
- Microfiltration

These new techniques alone may now be sufficient to meet used oil analyses objectives, but controversy says look at viscosity and pH also.

48. No Author, Proceedings, "Rapid Methods for the Analysis of Used Oils, Papers presented at a joint AFTP-SIA Meeting on 12 October 1970, Published by Scientific Publications.

(a) Collat, R. (Mobil Oil Francaise), "Rapid Laboratory Methods, Differential Infrared and Calibrated Membrane Filtration."

Calibrated membrane filtration gives more realistic data on lubricant quality than conventional centrifuge insolubles. Differential infrared as a single test gives information on contamination and chemical changes including water, ethylene glycol, oxidation products, nitration, fuel dilution, and additive peak changes.

(b) Morot-Sir, F. (Societe Francaise des Petroles BP), "Application of Thin-Layer Chromatography to the Analysis of Additives in Lubricants."

Identification and quantitation of lubricant additives and ethylene glycol contaminant are possible using an optical density meter.

(c) Sibenaler, E. (Ecole Royale Mililaire de Bruxelles), "The Photometric Analysis of Blotter Spot Tests."

The blotter spot test, behavior of oil spot, theory of photometric methods, practical illustrations, advantages and disadvantages are discussed in depth. Approach is felt to be effective, sensitive, and accurate for controlling crankcase oil quality and dispersancy. Mathematical description of spot tests and their interpretation for oil condition are given.

(d) Perrier, P. (Minisilere de la Marine Nationale), "The French Navy STM Control Kit."

Shipboard personnel control used lubricant testing and interpretations using a rapid test kit for essential parameters of dilution, acidity, and contamination.

- Dilution is appraised by a balldrop viscosity comparator method with improved accuracy over the standard viscosity comparator.

- Acidity is measured by the variations of a colored marker (the purple green of bromocresol) in an aqueous solution:

pH	Aqueous Phase Color
4	yellow
5-6	green
7	purple

- Contamination by blotter spot test using a maximum insolubles content corresponding to a spot with an intensity of 4 on the Munsel scale with perfectly standardized paper (Durieux 122). Sample spots with coloration of 5½ and 9 (on the Munsel scale) corresponding to moderately and slightly polluted oils, respectively, provide the user with examples of spot coloration progression for comparison. The intensity of 4 has been correlated to a heptane-coagulated insolubles level of 2 percent.

(e) Gourlaouene, A. (Esso Standard SAF), "Rapid Analysis Methods for Used Oils in Sevice Equipment."

Practical rapid tests in a portable kit are described in addition to criteria for determining the need for oil change. Tests will include:

- Acidity by methanol extraction and blending with pH-color indicator or pH paper (less desirable).
- Viscosity by falling sphere technique correlated to ASTM D 445.
- Water content using Watersmo paper sensitive to water. The paper dipped into the oil and withdrawn will develop blue spots:

No. of Blue Spots per cm	Water Content, wt%
No spots	0.5
1 or 2	0.5
about 5 spots	1.0
above 10 spots	2.0

When using Hydrokit Powder:

No. of Purple Spots	Water Content, ppm
1 or 2	20-40
5 to 10	40-60
Numerous	60-200
Purple stretches	200-500
Entirely purple powder	500

- Sediment content for hydraulic and compressor oils by mixing with heptane and evaluating its spot on 8 micrometer Millipore paper.

- Carbon content by simple photometer opacity of sample in a tube versus a standard. A 3-percent carbon value considered as a limit. May indicate poor stoichiometry or other piston area engine deficiency.

- Detergency by blotter spot test using the dark zone spread to indicate degree of detergency.

- Dilution by fuel indicated by viscosity when carbon content not off-setting.

(f) Moro, F. (Compagnie de Raffinage Shell Berre), "In-Service Testing and Lubrication Monitoring," p 45.

Gasoline engine oils for a fleet of taxis are compared to bench-test results. Blotter spot test indications at 20° and 200°C predict engine failure and faulty running. Glycol contamination is deceiving if continuous in that soot level in used oil does not increase. Some very good examples of water/glycol contamination in diesel engine oil are given which show the drastic decrease in dispersancy, resulting in a flocculated spot of irregular contour.

(g) Illien, J. (Direction du Materiel de Transport des PTT), "The Viewpoint of a Large Motor-Pool Operation," p 69.

Rapid oil analysis methods for used oils must be easily done by nonspecialized staff to determine both oil change frequency and improper engine running conditions so as to keep the engine clean and to promote long engine life. Such rapid tests of a practical applicability for promotion on a generalized scale do not now exist.

(h) VanLaer, R. (Ecole Royale Mililaire de Bruxelles), "A Brief Look at the Activities of the CL9 Project Group of the CEC Engine Monitoring Group," p 71.

Objective is to find simple, fast, and economical methods of analysis so as to spot anomalies of a mechanical nature or related to fuel or oil. Base number and infrared analysis subgroups are actively developing techniques.

(i) Amprimoz, L. (Services des Essences des Armes), Engine Monitoring by Spectrometry," p 75.

As part of a joint program by countries affiliated with NATO, a SOAP agency was created with aims to develop (1) a technique for controlling oil condition and (2) a method for quickly detecting abnormal engine wear. Spectrometric methods include infrared and atomic absorpton and are in early stages of development at the time of this report.

49\. Williams, W.T. (Sun Oil Co.), "Field Test Kit for Evaluating Lubricants in Service," <u>Lubrication Engineering</u>, <u>33</u>, 4, pp 191-194, April 1977. Particular attention is given to sampling, testing, and evaluating results.

- <u>Sampling</u>: Same place each time while oil is at operating temperature prior to make-up oil addition into a clean dry bottle shaken prior to withdrawal for testing.

- <u>Viscosity</u>: Single most important test done by falling ball comparator at ambient temperature correlated to viscosity at 100°F.

- Total Acid Number: Miniaturized ASTM D 974 test by titration.
- Blotter Spot Test: Determine amount of dirt (soot, sludge, etc.) present and the dispersancy that is left.
- Insolubles: Oil (1 ml) is put through 0.5-micrometer filter paper and washed with naphtha. The color and density of the resulting filter are visually matched to standards.
- Glycol Test: Standard procedure for detection in four ranges up to 1,000 ppm.
- Water Test: Several drops of oil in aluminum dish are heated by match, candle, etc. If bubbling or spotting occurs, indicates presence of water.

50. No Author, Military Specification, MIL-T-19467C, "Testing Kit, Internal Combustion Engine In-Service Oil Condition."

    Scope: Test kit estimates
    (1) Dilution with fuel (viscosity comparison)
    (2) Viscosity increase (oil thickening)
    (3) Reaction (presence of corrosive acids)

51. Gates, V.A., Bergstrom, R.F., Hodgson, T.S., and Wendt, L.A. (Shell Oil Company), "On the Spot Testing of Used Lubricating Oils," SAE Preprint Paper No. 339, presented August 16-18, 1954.

    Describes in detail the spot, indicator, and interpretation of the "Spot Test" for:

    (1) Oil contamination
    (2) Dispersant effectiveness
    (3) Alkalinity level

52. Gates, V.A., Bergstrom, R.F., and Wendt, L.A. (Shell Oil Co.), "Further Discussion on 'Oil Spot' Evaluation of Used Engine Lubricants," SAE Preprint Paper No. 572, presented August 15-17, 1955.

53. Badiali, F.L., Berti, F., Ingoni, A.A.C., and Persateri, G., "Evaluation of Dispersancy by Analytical Methods," SAE Paper No. 780932.

    This paper emphasizes the advantages of microfiltration, centrifuging and photometry, and acid spectrophotometry in evaluating dispersancy, although these methods are far from being rapid.

III. OIL ANALYSIS AND FERROGRAPHY

Ferrography is gaining in popularity both in the laboratory and as a field "tool" for wear diagnostics (42-44 and 54-64). While the quantity of material on a ferrogram tends to relate to the degree of wearmetal production, the appearance (size and configuration) relates to the type of wear and the component wearing. In addition to the type or nature of wear occurring, corrosion processes can also be identified. An "atlas" of wear and corrosion particles for diagnostics is slowly developing. Since these metallic particles of diagnostic significance in defining the type of impending failure are generally not large enough to be seen without a microscope, the ferrographic procedure has been slow to move from the research laboratory to general engineering practice or into the field (at the maintenance level) where it would be most effective. Additionally, magnetic chip detectors (collectors) and oil filters tend to "catch" a portion of those particles in an oil which would have been a part of the ferrographic analysis. Hence, microscopic examination of particles on magnetic chip collectors and on filter elements on a routine basis can improve detection and diagnostics when used in conjunction with other detection techniques.

Ferrographic analytical techniques and their application warrants close review and continued attention as ferrography becomes potentially more attractive in the diagnostics of engine component wear. It is now more of a research tool, but "tomorrow," it may be the diagnostic tool providing better OAP success rates and lower OAP fail rates.

54. Johnson, J.H., "Monitoring of Machine Wear by Used Oil Analysis," Presented at International Conference on Fundamentals of Tribology, held at MIT, June 19-22, 1978.

    Future research and development work is required to further understand ferrography measurements. Standardized ferrography quantitative parameters such as severity index must be resolved in the future in order to develop a baseline of ferrography data. Effects of oil sample test volume, oil consumption, and oil addition must be considered. Oil sample collection, ferrogram preparation, and analysis and parameter calculation procedures need to be standardized if an orderly technological transfer from the research lab to engineering practice is to occur.

By comparison, spectroscopy measures total particle concentration from all surfaces by element whereas ferrography measures percent area covered by particles on ferrogram by size with emphasis on particles greater than 1-micrometer.

55. Hofman, M.V., and Johnson, J.H., "The Development of Ferrography as a Laboratory Wear Measurement Method for the Study of Engine Operating Conditions on Diesel Engine Wear," Wear, 44, pp 183-199, 1977.

Using a Cummins VT-903 engine, the ferrographic oil analysis severity index appears to be applicable to the detection of slight changes in wear rate due to engine-operating conditions. Heated ferrogram analysis techniques enable monitoring of slight changes in the wear rates of various ferrous wear surfaces, a capability unattainable by spectrographic analysis only. Actually the heated ferrographic analysis represents a breakthrough in the wear analysis of specific engine components previously only possible using radioactive tracer wear analysis methods. The ferrographic oil analysis severity index appears to not only correlate well with atomic emission spectroscopy but also offers greater sensitivity and wear component specificity.

While inlet oil and outlet coolant temperatures tend to increase wear levels, other data suggest the fuel consumption levels are improved. Accurate temperature control selection could produce optimized reductions in fuel consumption and total engine wear. Listed in order of importance to engine development wear considerations are:

- Main bearings
- Connecting rod bearings
- Camshaft bushings
- Camshaft
- Tappet roller pins
- Tappet rollers
- Piston rings
- Cylinder liner
- Valve guides
- Piston ring bushings
- Crankshaft

with the main bearings, cylinder liners, and crankshaft dominating heated ferrogram analyses and examination of engine parts. Note that some of the components have different types of iron identifiable by ferrographic analysis (using microscopic techniques) but not separable by spectrographic techniques. Note also that the VT-903 cast iron piston rings and cylinder liner are not universal in all diesel engines.

56. Westcott, V.C. (Trans-Sonics, Inc.), "Ferrographic Oil and Grease Analysis as Applied to Earthmoving Machinery," SAE Paper No. 750555.

The author emphasizes the advantage of ferrographic analysis over spectrographic analysis in providing determination of the nature of an impending failure through particle size and type. Wear particles belong to certain unique classes of wear and certain types of wear particles are associated with specific modes of wear, thus allowing prediction of an abnormal wear-mode progression.

57. Hofman, M.V. and Johnson, J.H., "The Development and Application of Ferrography to the Study of Diesel Engine Wear," SAE Paper No. 780-181.

Paper provides an extensive list of references (a total of 55) which includes the Navy's programs, Foxboro Analytical's ferrograph, etc. The authors identify the research and development nature of ferrography as well as the practical use of simple ferrography on shipboard and maintenance shop levels as a diagnostic tool.

58. Anderson, D.P. and Silva, R.S. (The Foxboro Company),"The Direct Reading Ferrograph Design, Calibration and a Field Application," ASLE, 35, 4, pp 203-211, (April 1979).

Comparison of ferrographic data and spectrometric data on the same oil samples is made, and typical field applications are discussed.

59. Scott, D. and Westcott, V.C., "Predictive Maintenance by Ferrography," Wear, 44, pp 173-182 (1977).

Wear particles through ferrography can be a reflection of machine wear mechanisms.

60. Suh, N.P., "An Overview of the Delamination Theory of Wear," Wear, 44, pp 1-16 (1977).

61. Bowen, R. and Westcott, V.C., "Wear Particle Atlas," Foxboro/Trans Sonics, Inc., Burlington, MA, 01803. Prepared for Naval Air Engineering Center, Lakehurst, New Jersey, 98733, July 1976.

Wear particles have characteristic shapes.

62. Scott, D., McCullough, P.J., and Campbell, G.W., "Condition Monitoring of Gas Turbine--An Exploratory Investigation of Ferrographic Trend Analysis," Wear, 49, pp 373-389 (1978).

Successful application of ferrographic analysis to trend analysis/wear diagnostics of gas turbine engines was demonstrated.

63. Scofield, G.L. (1977 SAE President), "Diesel Engines and Their Particle Signatures," SAE Paper No. 780426.

Use of ferrography and scanning electron microscopy to analyze particles of wear is demonstrated by specific examples.

64. Beerbower, A. (Exxon Research and Engineering Co.), "Spectrometry and Other Analysis Tools for Failure Prognosis," Lub. Engineering, 32, 6, pp 285-293, June 1976.

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